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SOIL SCIENCE

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CATION EQUILIBRIA IN PLANTS IN RELATION TO THE SOIL

TH. B. VAN ITALLIE

State Agricultural Experiment Station, Groningen, Netherlands

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Fundamental investigation of cation equilibria in the plant in relation to the composition of the soil must be carried out in solution cultures or sand cultures in which the substrate is strictly controlled during the experiment. In applying the results of such fundamental experiments to plants grown in the soil, many difficulties are encountered (3). In working with soil solutions these difficulties are only partly solved, because the natural conditions in the soil—a soil solution in equilibrium with a solid phase—can be only partly imitated; for that purpose the addition of colloidal matter to the solution or sand culture has been tried (1, 4).

From an agricultural point of view, now that so much fundamental work on the ion uptake of plants has been done by plant physiologists, the most promising method is: first to study the plant growth and the uptake of ions under soil conditions that are as strictly defined as possible, then to correlate a large quantity of experimental data for soil and plant, and finally to try to elucidate the results on the basis of conclusions drawn from general physiological work (5).

The purpose of this paper is to offer a contribution to the study of this problem through a discussion of some pot culture experiments on soils with greatly varying amounts of added cations, both plant growth and cation content of the plants being studied.

EXPERIMENTAL

In these experiments an attempt is made to minimize the influence of the exchangeable cations already present in the soil: *a.* by choosing acid soils with a low degree of saturation of the adsorption complex with basic ions; *b.* by adding amounts of cations large in comparison to those already present in the soil.

The advantages of this scheme are that one is as independent as possible of the original cation ratio in the soil and has the opportunity to establish new cation ratios, including extreme cases. As a basis of calculation for the cation content of the soil to be brought into relation with the uptake by the plants, the cations that were added in the form of carbonates—to effectuate exchange with the H ions of the adsorption complex—are added to the cations already present in solution and in exchangeable form, as determined by extraction of

the soil by 0.1*M* HCl (1:20). It is assumed that the exchangeable and dissolved cations will be available to the plant in the same way and to the same extent as are those added to the soil in the form of carbonates. This assumption is more or less arbitrary, but since we have no exact notion as to the availability of the cations in different forms in the soil, we may as well take this assumption as a working hypothesis. In all our diagrams, therefore, we plot the cation content of the plant against the total sum of the exchangeable cations present in the soil. The discussion of our first experiment, described in this paper, will serve as a good example of the principle followed in this series of experiments.

We took an acid sandy soil, rich in humus (13 per cent), with a pH in aqueous suspension of 4.3 and a total saturation capacity (*T*-value) of 28 m.e. in 100 gm. soil, of which 8.5 m.e. (30 per cent) was saturated by the sum of the cations Ca, Mg, K and Na. The sum of cations added, for all treatments, amounted to 7 and 14 m.e. respectively, which raised the degree of saturation theoretically to 55 and 80 per cent respectively. The amount of each of the cations present in the soil and added separately or in different combinations, is given in table 1, in which the complete data on this experiment are brought together.

The experiment was carried out with two parallel series in Mitscherlich culture vessels containing about 5 kgm. of air-dried soil. After the carbonates were thoroughly mixed with the soil, a hundred seeds per pot of "Westerwoldsch raaigras" (*Lolium italicum westerwoldicum*), a very productive Dutch strain of Italian rye grass, were sown on April 9, 1934. As a basal dressing, each pot received 1.17 gm. of secondary ammonium phosphate (about 80 kgm. N and 200 kgm. P_2O_5 per hectare). The soil was maintained throughout the experiment at a water capacity of about 50 per cent of the maximal.

After coming up on April 17, the grass showed such a vigorous growth that a first cut could be taken on May 16; a second cut was taken on June 8 but not studied further, as the aftergrowth had been irregular because of the great differences in yield of the first cut.

From the first two columns of table 1, we see that the cations were given separately in single and double amount and also combined in pairs in half and single amount; four pots received further combinations of Mg, K, and Na and of all four cations together.

In the next five columns of table 1 are shown the amounts of cations present in 100 gm. of soil after the addition of the carbonates. Calcium occurred in the soil in an amount about equal to that of the single addition of carbonate, but the single and double applications of the other cations are very large in comparison with the amounts present in exchangeable state in the original soil. We added such large quantities, not only to be independent of the cation ratio in the original soil, as has been stated, but also to alter the degree of saturation of the adsorption complex with Mg, K, and Na in a manner similar to that in

TABLE 1

Soil values and yield and cation content of Italian rye grass in a pot experiment

TREATMENT	CATIONS						pH OF THE SOIL, END OF EXPERIMENT	YIELD OF GRASS*	CATIONS PRESENT IN 100 GM. GRASS*				
	Added in the form of carbonate	Present in 100 gm. soil											
		Ca	Mg	Na	K	Sum			Ca	Mg	Na	K	Sum
		m.e.	*m.e.*	*m.e.*	*m.e.*	*m.e.*		*gm.*	*m.e.*	*m.e.*	*m.e.*	*m.e.*	*m.e.*
0	0	6.7	1.1	0.3	0.4	8.5	4.8	9.8	17	24	11.5	133.5	186
1 Ca	7	13.7	1.1	0.3	0.4	15.5	6.0	8.5	35.5	26.5	12.5	129	203.5
2 Ca	14	20.7	1.1	0.3	0.4	22.5	6.6	5.0	39	25.5	12	124	200.5
1 Mg	7	6.7	8.1	0.3	0.4	15.5	5.6	8.0	14	49	9.5	123	195.5
2 Mg	14	6.7	15.1	0.3	0.4	22.5	6.7	7.8	11.5	62.5	9	112	195
1 Na	7	6.7	1.1	7.3	0.4	15.5	6.4	5.8	8	17.5	97	78.5	201
2 Na	14	6.7	1.1	14.3	0.4	22.5	7.4	....	....	....	....	....	.....
1 K	7	6.7	1.1	0.3	7.4	15.5	6.5	5.5	8	17.5	13	169	207.5
2 K	14	6.7	1.1	0.3	14.4	22.5	7.3	....	....	....	....	....	.....
½ Ca + ½ Mg	7	10.2	4.6	0.3	0.4	15.5	5.8	7.3	23	36	15	123	197
1 Ca + 1 Mg	14	13.7	8.1	0.3	0.4	22.5	6.5	7.0	24.5	47	10.5	130.5	212.5
½ Ca + ½ Na	7	10.2	1.1	3.8	0.4	15.5	6.1	10.5	18	22.5	61.5	103	205
1 Ca + 1 Na	14	13.7	1.1	7.3	0.4	22.5	7.2	8.0	13	22	93.5	78.5	207
½ Ca + ½ K	7	10.2	1.1	0.3	3.9	15.5	6.2	6.0	14.5	20.5	8.5	159	202.5
1 Ca + 1 K	14	13.7	1.1	0.3	7.4	22.5	7.1	6.0	11	18.5	6	163	198.5
½ Mg + ½ Na	7	6.7	4.6	3.8	0.4	15.5	6.2	7.3	10.5	31.5	58.5	99	199.5
1 Mg + 1 Na	14	6.7	8.1	7.3	0.4	22.5	7.0	5.8	7	27.5	88.5	72	195
½ Mg + ½ K	7	6.7	4.6	7.3	3.9	15.5	6.2	11.0	10.5	29	16.5	159	215
1 Mg + 1 K	14	6.7	8.1	7.3	7.4	22.5	7.2	5.0	6	23.5	7	152	188.5
½ Na + ½ K	7	6.7	8.1	3.8	3.9	15.5	6.6	5.8	6.5	18.5	35	122.5	182.5
1 Na + 1 K	14	6.7	8.1	7.3	7.4	22.5	7.3	....	....	....	....	....	.....
⅓ Mg + ⅓ Na + ⅓ K	7	6.7	3.43	2.63	2.73	15.5	6.2	9.8	9.5	27	31.5	137	205.5
⅔ Mg + ⅔ Na + ⅔ K	14	6.7	5.76	4.96	5.06	22.5	7.2	6.3	4.5	22	33	133	192.5
¼ Ca + ¼ Mg + ¼ Na + ¼ K	7	8.45	2.85	2.05	2.15	15.5	6.4	9.3	13	24	18.5	148.5	204
½ Ca + ½ Mg + ½ Na + ½ K	14	10.2	4.6	3.8	3.9	22.5	7.1	8.3	8	24	27.5	139.5	199

* Dry matter of first cutting.

ordinary practice for Ca, when such an acid soil is limed with fairly large amounts of calcium carbonate.

The pH values of the soil, given in the next column of table 1, were determined at the end of the experiment. The pH of the original soil was 4.3 at

the beginning of the experiment and 4.8 afterward. Compared with this latter value, the single amount of calcium and magnesium carbonate raised the pH, on the average, 1.0 unit, the double amount, 1.8; the single amount of potassium and sodium, raised the pH 1.7 units, the double amounts, 2.6.

It was to be expected that the large quantity of cations, especially of K and Na would cause serious disturbances of the growth. In three pots; namely, those receiving 2 K, 2 Na, and 1 K + 1 Na, the plants showed a very poor growth from the beginning and were almost completely destroyed before the first cutting. The plants from the pots receiving single additions of K and Na, separately and in combination, also showed a poor growth, as will be seen from the yields listed in table 1. In general, the yields from pots with double amounts of carbonate are less than those from pots with single quantities, and the latter are somewhat lower than the yield from the untreated pot, with three exceptions.

DISCUSSION

Table 1 shows that the additions of cations to the soil cause very considerable variations in the Ca, Mg, Na, and K content of the plants. Notwithstanding these large variations for the single ions, the sum of the four cations remains approximately constant, ranging from 182.5 to 215 m.e., 14 of the 22 values lying between 195 and 205 m.e. We may conclude, therefore, that in this experiment the mutual replacement[1] of the cations in the plant was nearly equivalent.

A better impression of the changes in composition of the plants can be obtained from figures 1–3, in which the amount of the four cations in the plants are plotted against the cation concentrations in the soil, as mentioned in table 1. In each diagram the values for the check and for the single, and the double addition (indicated by overlining), when present, are connected by a line; the points for the other pots are indicated as far as possible.

From figure 1 we see that the amount of calcium in the plant is doubled when a single amount of calcium carbonate is added; the double application gives only a small additional rise. The addition of magnesium in addition to calcium distinctly lowers the Ca uptake, whereas Na and K additions and all combinations containing these ions, with or without calcium, lower the calcium content, in general, to values below the value of the check.

From figure 2 we see that the check plants contain more magnesium than calcium; the rise as a result of the application of single or double quantities of Mg is also greater than that for calcium. In contrast with the influence of magnesium on calcium, Ca application does not distinctly lower the Mg content. The effect of sodium and potassium on magnesium shows the same course as that on calcium, i.e., low Mg values with Na and K carbonate without Mg, somewhat higher values when the alkali ions are given together

[1] We prefer the term "replacement" to "antagonism," when only the phenomenon of a mutually influenced increase and decrease of different ions is meant and not a physiological or a toxic effect on the plant.

with magnesium in small quantities, and again lower values for the treatments 1 Mg + 1 Na and 1 Mg + 1 K. For both calcium and magnesium, we find a greater depression from applications of K than from those of Na.

Figure 3 gives a totally different aspect for the Na uptake. All treatments without sodium show low Na values in the plant, without regular differences;

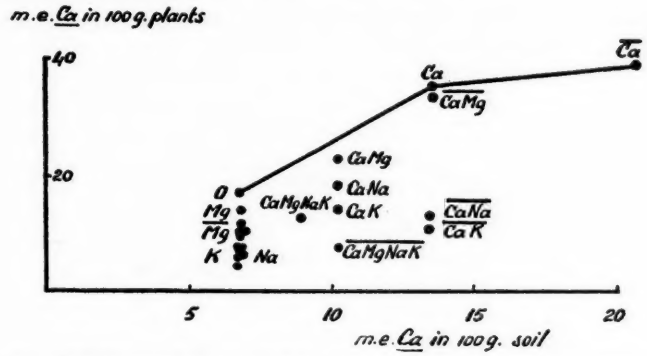

FIG. 1. RELATION BETWEEN EXCHANGEABLE CALCIUM IN THE SOIL AND ITS CONCENTRATION IN THE PLANT

The treatments containing double amounts of cations are overlined in all figures in this paper

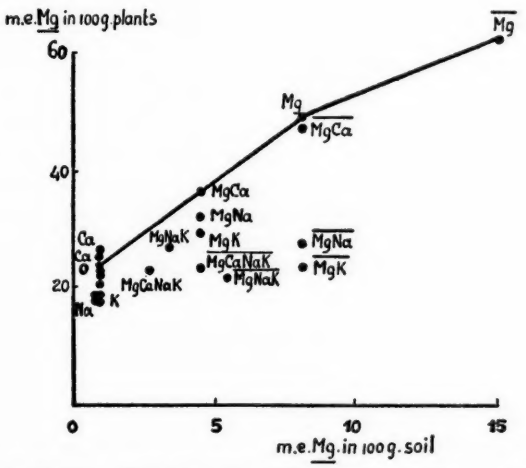

FIG. 2. RELATION BETWEEN EXCHANGEABLE MAGNESIUM IN THE SOIL AND ITS CONCENTRATION IN THE PLANT

Na application, however, raises the Na content to very high values. The depressions caused by additional Ca and Mg applications are visible, but of little importance; all combinations of potassium and sodium give a very considerable lowering of the Na content in comparison with sodium application

without potassium. We get the impression, from the values for the combinations containing smaller amounts of sodium, that the Na line is slightly curved; this is true also for the K line.

For potassium, figure 3 again shows quite another aspect. Potassium in the plant is high for the check, as the untreated soil is not very deficient in K; the single K application produces a still higher value, although this increase in K uptake is proportionally much smaller than the increases in the corresponding

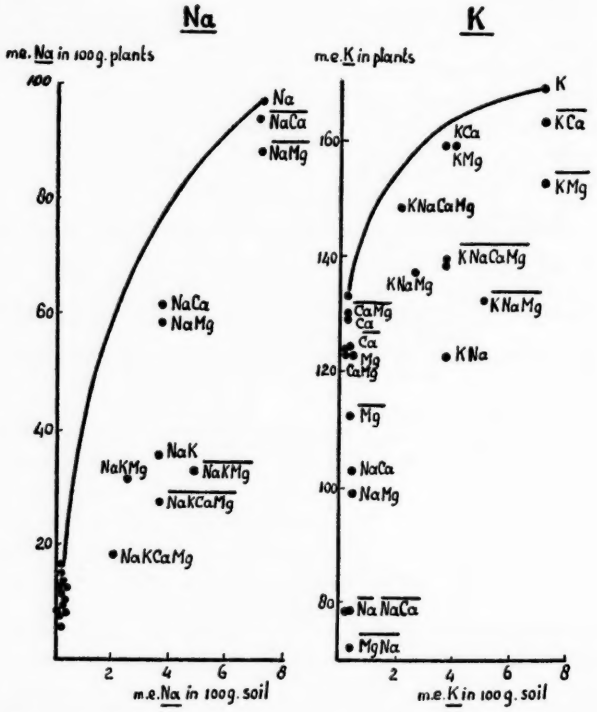

FIG. 3. RELATION BETWEEN EXCHANGEABLE SODIUM AND POTASSIUM IN THE SOIL AND THEIR CONCENTRATIONS IN THE PLANT

cases for Ca, Mg, and Na. The Ca treatments, with or without potassium, give K values that do not deviate greatly from the curve; in all cases magnesium distinctly lowers the K values, if compared with the treatments without Mg. The greatest depression of the K content is found, however, with Na application, alone or combined with calcium and magnesium. Without potassium addition, we find in these cases very low K values for plants; when equal K and Na are applied, potassium is held more or less in equilibrium when com-

pared with the uptake from the original soil; with greater additions, however, the K content is again lowered.

In comparing the amount of each ion in the plant for the pot treatment in which the particular ion is present in exchangeable form in the soil in amounts of 6.7 to 8.1 m.e., we see that potassium is the most readily absorbed; sodium, magnesium, and calcium then follow successively, a sequence which has been observed in many other investigations including solution-culture experiments. As we find almost equivalent replacement of one ion by the others, it is clear that application of the ion that is taken up most easily, namely, K, will exert the greatest depressive action on the other ions. This fact can be clearly seen in the graphs for Ca, Mg, and Na. A decrease in the depressive action of the Na, Mg, and Ca ion is visible for each of these ions respectively in three of the four diagrams.

Under normal conditions, we find in all soils, at least under our climatic conditions, a great excess of exchangeable calcium as compared with the other basic ions, whereas the amount of magnesium usually exceeds that of potassium and sodium. In many soils the excess of Ca is much greater than that in the soil with a low degree of saturation used in this experiment. It will be clear that the changes in the cation uptake, caused by the different ion applications, are controlled to a considerable extent by the original cation ratio, although our additions, at least of K and Na, are so large that the amounts of these ions present in the original soil, can almost be neglected. Exchangeable sodium and potassium, for instance, are present in the soil in almost equal amounts; this K-Na ratio is sufficient for an abundant K uptake, whereas it results in only a very small Na uptake. If, then, we add potassium alone or in combination with calcium and magnesium, the K in the plant increases considerably and replaces part of the Ca and Mg, the Na content being already so low that no appreciable further decrease takes place. If, however, sodium alone or combined with calcium and magnesium is added, the originally low Na value rises much more than potassium did in the former case; but in this instance not only calcium and magnesium but, above all, the high content of K is lowered by replacement because of the important Na uptake. Thus an equal addition of both alkali ions causes a much greater change in the conditions for uptake of sodium than for potassium, because from the original soil a large amount of K, but only a small amount of Na, has already been taken up.

In a similar way, we can compare the Ca and Mg uptake. Calcium added in an amount about equal to the excess already present in the soil and taken up with the greatest difficulty by the plant, does not cause great variations in the composition of the plant and therefore does not play an important part in ion replacement. The same amount of magnesium, added to the soil containing only relatively little Mg, naturally causes a greater change in the ratio of magnesium to the other ions and has, therefore, a greater influence on the com-

position of the plants, because from an equal application more magnesium than calcium is taken up.

In reviewing the results of this experiment, it is evident that, generally, the uptake of a cation cannot be brought into simple relation with the concentration of that ion in the soil in any form, but that it must be regarded as dependent upon the ratio of that ion to the others in the soil. Other influences, for example, that of the anions on the cation uptake, need not to be discussed here, because these have been ruled out in this experiment. It may perhaps seem strange that, in fertilizing experiments, the ion concentration in the soil should not be the principal factor controlling the ion uptake, but one must bear in mind that in ordinary experiments, as a rule, only the concentration of the particular ion being studied is changed; the ratio of the other ions remains the same and need not to be taken into consideration. If, however, we compare crops grown on soils with greatly differing cation ratios, we may conclude that in such cases these ratios will certainly be of special importance.

When not only the concentration of the ion studied, but also that of the other cations in their ratio to that ion, is involved, it will, of course, be much more difficult to find a satisfactory relation between soil values and ion uptake. Burström (2) was the first to study quantitatively in solution cultures the uptake of one ion, when the concentration of another anion was varied and the concentration of the ion studied remained constant. The results of his experiments can not, as yet, be applied to soil conditions. Our experiments, however, with more or less extreme conditions as regards the cation ratio, gave us the opportunity to study this complicated relationship between the ion uptake and the variations in the amounts of all four cations in the soil. We did not intend to establish exact rules about this relationship, but only tried to find, for each ion separately, a value in the soil which would be more closely related to the composition of the plant than the simple concentration value plotted on the abscissa in figures 1–3.

One of the ways of taking all ions into account is by expressing the cations in the soil in percentages of the sum of Ca, Mg, Na, and K, because, in so doing, the addition of one cation always affects the percentage figure of all four. When expressing the amount of cation in percentage figures, we make no allowance, however, for the great differences in the influences of each cation on the others. It will be evident that these differences can be brought into consideration by giving to each ion a special coefficient, with which its concentration in the soil must be multiplied before it is brought into relation with the concentrations of the other ions.

Taking also into consideration the figures obtained in other experiments on different sandy soils, we worked out for the present experiment the following coefficients, which gave the best correlation for each ion with the values found in the plants: Ca, 1; Mg, 2; Na, 10; K, 20.

Using these coefficients, we established the following relationships for the values in the soil, to be correlated with the cation uptake by the plants:

$$\text{For Ca: } \frac{\text{Ca}}{0.2\,\text{Mg} + \text{Na} + 2\,\text{K}}$$

$$\text{For Mg: } \frac{2\,\text{Mg}}{0.1\,\text{Ca} + \text{Na} + 2\,\text{K}}$$

$$\text{For Na: } \frac{10\,\text{Na}}{0.1\,\text{Ca} + 0.2\,\text{Mg} + 2\,\text{K}}$$

$$\text{For K: } \frac{20\,\text{K}}{0.1\,\text{Ca} + 0.2\,\text{Mg} + \text{Na}}$$

To obtain figures that are more convenient for use, the decimals in numerator and denominater are chosen differently. We do not claim that the for-

TABLE 2

Values of magnesium obtained by formula

TREATMENT	MAGNESIUM PRESENT IN THE SOIL			Mg IN PLANTS, M.E. PER 100 GM. DRY MATTER
	In m.e. per 100 gm.	In per cent of sum	Determined by the formula	
0	1.1	13	1.18	24
1 Ca	1.1	7	0.80	26.5
1 Na	1.1	7	0.24	17.5
1 K	1.1	7	0.14	17.5
1 Mg	8.1	52	8.70	49
1 Mg + 1 Ca	8.1	29.5	5.86	47
1 Mg + 1 Na	8.1	29.5	1.82	27.5
1 Mg + 1 K	8.1	29.5	1.02	23.5

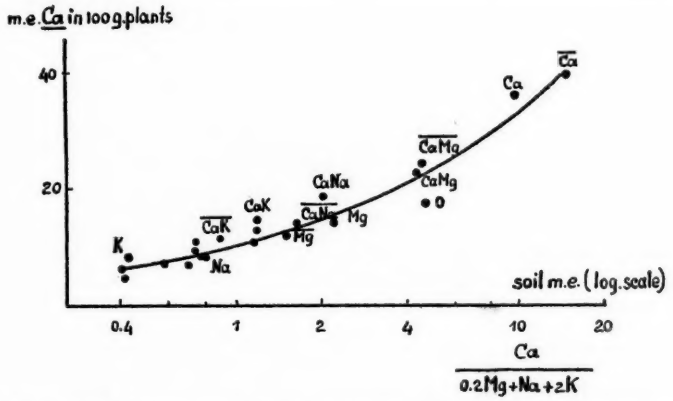

FIG. 4. RELATION BETWEEN THE SOIL VALUE FOR EXCHANGEABLE CALCIUM, CALCULATED BY THE GIVEN FORMULA, AND THE CONCENTRATION IN THE PLANT

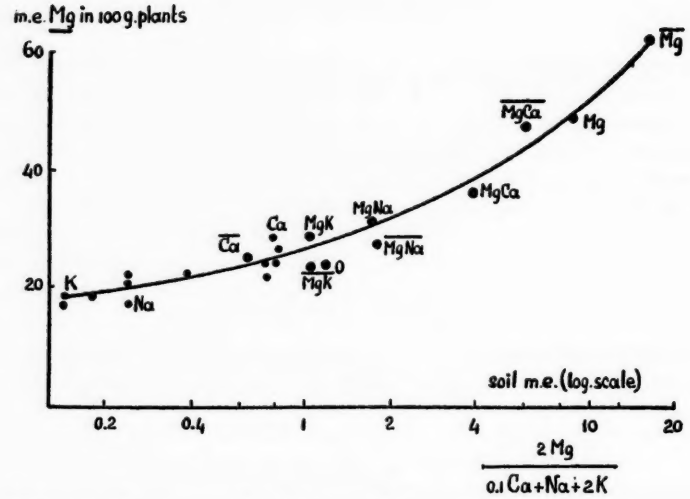

FIG. 5. RELATION BETWEEN THE SOIL VALUE FOR EXCHANGEABLE MAGNESIUM, CALCULATED BY THE GIVEN FORMULA, AND THE CONCENTRATION IN THE PLANT

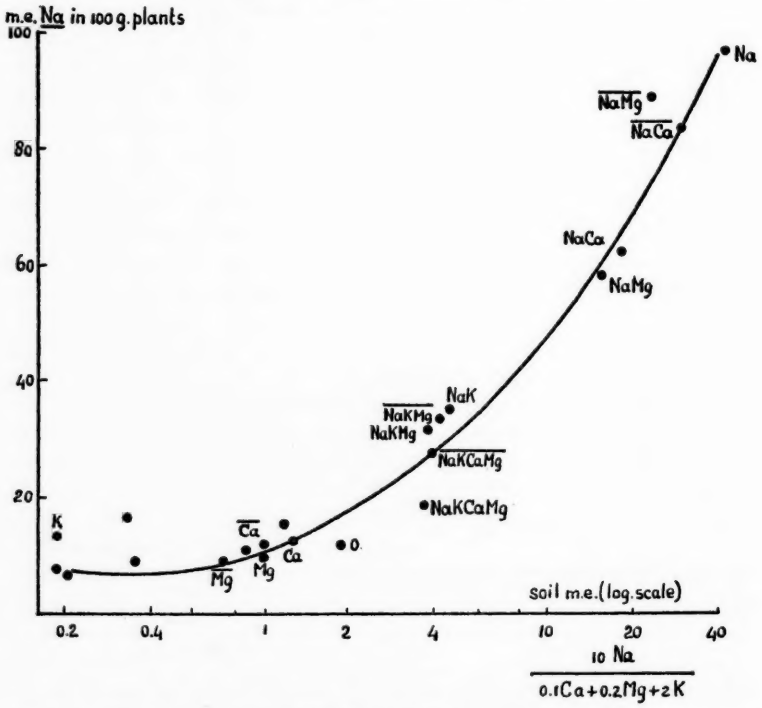

FIG. 6. RELATION BETWEEN THE SOIL VALUE FOR EXCHANGEABLE SODIUM, CALCULATED BY THE GIVEN FORMULA, AND THE CONCENTRATION IN THE PLANT

mulas given are the best for correlating the relations in the soil with those in the plants; they are meant only to indicate the order of magnitude with which each ion will affect its own uptake and that of the other three cations. In table 2 are given, as an example of some values obtained according to these formulas, the figures for eight treatments with magnesium in comparison with the Mg values from table 1 and when expressed in percentages of the four cations in the soil.

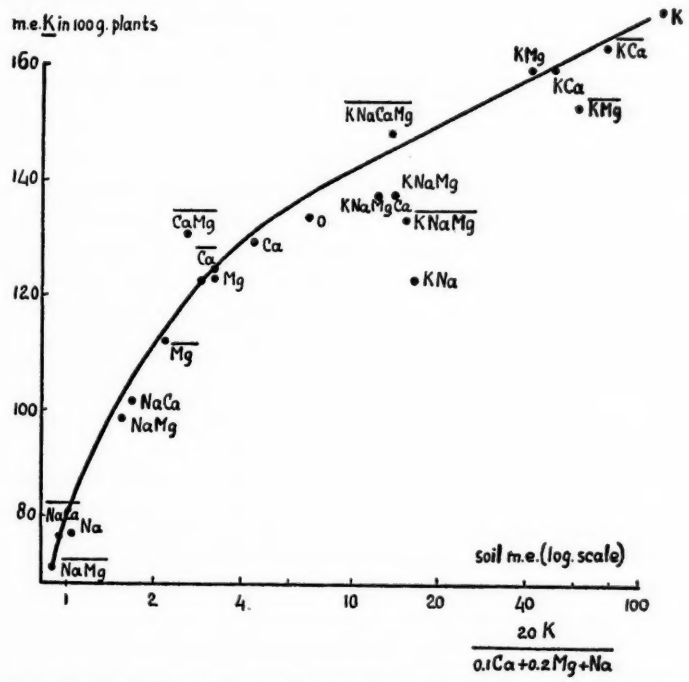

FIG. 7. RELATION BETWEEN THE SOIL VALUE FOR EXCHANGEABLE POTASSIUM, CALCULATED BY THE GIVEN FORMULA, AND THE CONCENTRATION IN THE PLANT

As can be easily seen from table 2, Mg in the plants correlates much better with the Mg values in the soil determined by our formula, than with those of the other columns. In figures 4–7 are plotted, for each cation separately, the soil values according to our formulas, for all treatments, against the ions in the plants, as was also done in the former diagrams. Because 17 of the 22 treatments for all ions gave soil values lying in the lowest sixth part of the scale, these values are plotted logarithmically, so as to bring out more clearly the position of the single points on the graphs.

These figures show that, with a few exceptions, there is a fairly close rela-

tionship between the soil values and those of the plants; this is shown by average curves. It is distinctly seen that, by giving to potassium 20 times, to sodium 10 times, and to magnesium twice the value of calcium, the values with Mg, Na, and K in the denominator are transferred in increasing measure to the left in the diagrams. The soil values fit to the curves much better than they do in figures 1–3.

The possible importance of using such formulas to establish a useful relationship between soil and plant values will be discussed on another occasion, when we hope to give more experimental facts about this subject. The conclusion to be drawn at present is that it seems possible to set up such a relationship, which we hope may be of some assistance in elucidating the complicated process of ion uptake from a soil.

SUMMARY

An experiment is described in which great changes in the ratio of Ca, Mg, K, and Na in a soil relatively poor in exchangeable cations are effected by the addition of large quantities of carbonates of these ions. The amount of cations in Italian rye grass, grown in pots on samples of this soil, supplied with different amounts of these cations, was studied. As was to be expected, great changes in plant composition were found under the influence of the varying ratio in the soil. The well-known mutual replacement of the cations in the plant took place in this experiment, for the most part, in nearly equivalent amounts, the uptake and the replacement value being largest for potassium and decreasing progressively for sodium, magnesium, and calcium. In consequence of this different replacement capacity of the four cations, one finds no satisfactory relationship between the concentration of an ion in the soil and that in the plant, even when concentration in the soil is expressed in percentage figures. By giving, however, to the concentration figure of each cation in the soil a special coefficient and taking the ratio of the soluble plus exchangeable amount of each ion and the same amount of the others, we obtained soil values which gave a satisfactory correlation with the composition of the plants. In a further paper, additional experimental results will be given, on its basis of this method of expressing the cation concentrations in the soil.

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FERTILIZATION IN ITS RELATIONSHIP TO THE COURSE OF NUTRIENT ABSORPTION BY PLANTS[1]

TH. REMY[2]

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INTRODUCTION

It is self-evident that, other things being equal, fertilizer needs increase with added nutrient needs of plants. The equality of these other factors, however, is easily deranged by the inherent thriftiness of the plants and their ability to extract nutrients from naturally occurring sources; the equally inherent distribution of the nutrient needs; and the reaction of the plants to modifications in soil conditions brought about by the various ingredients in the fertilizer. Thus the relationships between nutrient and fertilizer needs are, by no means, necessarily parallel. The purpose of this article is to delineate, on the basis of the aforementioned factors, the significance of nutrient needs and their distribution during the life of the plant, to the use of fertilizers.

It cannot be assumed that the nutrient needs of plants are the same as the nutrient contents of plants, for the following reasons:

Nutrient absorption varies with supply between two limiting values, one of which represents luxury consumption, the other a physiologically insufficient but not growth-inhibiting minimum.

An undetermined portion of substances absorbed during growth returns to the soil long before maturity, by root excretions or remigration, cuticular sloughing of living plant parts, and decay and lixiviation of dead parts.

The unharvested parts of plants contain nutrients which are not removed in the harvest.

If based on sufficiently numerous and reliable observations, however, nutrient contents afford an approximation of the nutrient needs of the species. In view of the great variation involved, certainly no more than an approximation of nutrient needs is to be obtained in this way, and for practical purposes of fertilization, anything more is not absolutely necessary. With a given need, the distribution over a period of time, or the course of nutrient absorption, is very much of a factor in determining fertilizer requirements. No sensible physiologist would deduce rules for the form of the daily fare from the fact that man in the course of 70 years requires x million calories in nutrition. The applicability of the rules assumes, among other things, adaptation of the supply to age, sex, type of work, climate, and other factors of life. Relatively,

[1] Translated from the German, by J. D. Romaine, chief agronomist, American Potash Institute, Inc., Washington, D. C.

[2] Formerly professor at Bonn University, Bonn, Germany.

the same thing holds true for plants. Nutrients must be not only sufficient for plants but also available at the right time. Such considerations have engendered numerous investigations on the course of nutrient absorption by plants.

LIEBSCHER'S TEACHINGS

In Germany, Liebscher was the first to draw attention to this question by a study published in 1887 (2). His conclusions may well be quoted herewith:

> In a comparison of the curves of organic matter with those of nutrient absorption [Liebscher plotted curves in his work on the course of nutrient absorption] we see very clearly in virtually every case, that
>
> (a) A relatively great increase in nutrient absorption during the young growing period of the plant indicates the necessity for supplying these nutrients in the readily soluble form of commercial fertilizers (grains, rape, etc.).
>
> (b) The steeper the rise of the curve for organic matter during the time of high nutrient needs, the greater is the need for the fertilizer roughly indicated under (a) above (barley, oats or horse beans, lupine).
>
> (c) Insignificant variability or approximate parallelism in the curves for organic matter and nutrient absorption indicates that the plants are dependent on the nutrients gradually going into solution. These nutrients are present in the soil as slowly decomposing residues from previous fertilization (clovers), or as nitrogen gradually added to the soil from the atmosphere (clovers and legumes).
>
> (d) A relatively steep increase of the nutrient curve toward the end of the growing period (potatoes, rutabagas, legumes) or an increased nutrient need which occurs in the middle of summer after a rather long period of slow growth, and thus at the time when reactions in the soil are very strong, is an indication that fertilization with barnyard manure, which decomposes slowly, is suitable for such plants (corn, sugar beets, legumes, cabbage, chicory).

LIEBSCHER'S TEACHINGS IN A CRITICAL LIGHT

Sickness and death (in 1896) terminated the work of Liebscher so early that he was not able to elaborate on his theory. Succeeding work participated in by the author, first as a pupil of Liebscher and later independently, furnished abundant detailed material for a critical examination of the problem. Unfortunately, however, this examination has long been postponed. The author explained the principles first in 1926 (1, 4, 5). Those statements are still valid but require supplementing on some points. It is sought, in the following sections, to reconcile these statements to present-day views.

Nutrient absorption during growth of plants

Observations on rye, which, as the most widespread field crop, is very frequently investigated in Germany, may serve as the starting point in the study of nutrient absorption during the growth of the plant. In spite of the difficulty due to their great diversity, the results of 6 experiments conducted by T. Roemer, of Halle (3), and of 18 of my own, have been reduced to a common denominator in table 1. As was to be expected, the nutrient absorption is correlated to some degree with the development of the rye. The same applies

TABLE 1

Growth and nutrient absorption of winter rye

PERIOD OF GROWTH	DETERMINATIONS										Least	Greatest	Average
	Roemer						Remy						
	1	2	3	4	5	6	1	2	3*	4*			
1. *Per cent of yield (dry matter) produced*													
1. Emergence to end of winter	4	3	2	2	2	2	8	1	2	2	1	8	2.8
2. End of winter to beginning of stalk growth	19	18	10	7	14	9	13	11	21	33	7	33	15.5
3. Beginning of stalk growth to blossoming	46	59	63	57	65	89	62	59	38	32	32	89	57.0
4. Blossoming to maturity	31	20	25	34	19	0	17	29	39	33	0	39	24.7
2. *Per cent of greatest amount absorbed*													
a. Nitrogen													
1. Emergence to end of winter	15	25	15	20	10	8	40	4	6	6	4	40	14.9
2. End of winter to beginning of stalk growth	37	20	45	31	24	18	19	35	19	70	18	70	31.8
3. Beginning of stalk growth to blossoming	25	35	30	28	58	74	41	44	34	17	17	74	38.6
4. Blossoming to maturity	23	20	10	21	8	0	0	17	41	7	0	41	14.7
b. Phosphoric acid													
1. Emergence to end of winter	8	8	8	8	13	8	17	2	3	3	2	17	7.8
2. End of winter to beginning of stalk growth	28	18	34	17	40	22	24	27	32	55	17	55	29.7
3. Beginning of stalk growth to blossoming	33	41	32	37	32	70	59	58	29	20	20	70	41.1
4. Blossoming to maturity	31	33	26	38	15	0	0	13	36	22	0	38	21.4
c. Potash													
1. Emergence to end of winter	10	10	7	10	9	8	12	2	3	3	2	12	7.4
2. End of winter to beginning of stalk growth	45	38	35	28	38	35	24	32	62	79	24	79	41.6
3. Beginning of stalk growth to blossoming	25	46	58	51	53	57	64	66	19	18	18	66	45.7
4. Blossoming to maturity	20	6	0	11	0	0	0	0	16	0	0	20	5.3
d. Lime (8 experiments)													
1. Emergence to end of winter	7	8	6	8	7	4	14	2			2	14	7.0
2. End of winter to beginning of stalk growth	25	22	25	20	26	18	18	24			18	26	22.3
3. Beginning of stalk growth to blossoming	44	55	59	53	52	78	68	63			44	78	59.0
4. Blossoming to maturity	24	15	10	19	15	0	0	11			0	24	11.8
e. Magnesia (2 experiments)													
1. Emergence to end of winter							15	2			2	15	8.5
2. End of winter to beginning of stalk growth							21	25			21	25	23.0
3. Beginning of stalk growth to blossoming							64	54			54	64	59.0
4. Blossoming to maturity							0	19			0	19	9.5

* Average of 8 independent observations each.

TABLE 2

Relative values for barley, rye, and wheat

PER CENT OF GREATEST AMOUNT FORMED OR ABSORBED TO	WINTER BARLEY	WINTER RYE	WINTER WHEAT	AVERAGE	PER CENT OF GREATEST AMOUNT OCCURRING IN GROWTH PERIODS	WINTER BARLEY	WINTER RYE	WINTER WHEAT	AVERAGE
I. Dry matter yield									
1. End of winter....	4	3	4	4	Emergence to end of winter.	4	3	4	4
2. Beginning of stalk growth.....	20	19	19	20	End of winter to beginning of stalk growth.....	16	16	15	16
3. Blossoming.....	77	76	78	77	Beginning of stalk growth to blossoming.....	57	57	61	58
4. Maturity.....	100	100	100	100	Blossoming to maturity....	23	24	22	23
II. Nitrogen									
1. End of winter....	16	15	16	16	Emergence to end of winter.	16	15	15	16
2. Beginning of stalk growth.....	43	47	43	45	End of winter to beginning of stalk growth.....	27	32	27	29
3. Blossoming.....	78	86	85	83	Beginning of stalk growth to blossoming.....	35	39	42	38
4. Maturity.....	100	100	100	100	Blossoming to maturity....	22	15	15	17
III. Phosphoric acid									
1. End of winter....	8	8	7	8	Emergence to end of winter.	8	8	7	8
2. Beginning of stalk growth.....	29	37	30	32	End of winter to beginning of stalk growth.....	21	29	23	24
3. Blossoming.....	73	79	79	77	Beginning of stalk growth to blossoming.....	44	42	49	45
4. Maturity.....	100	100	100	100	Blossoming to maturity....	27	21	21	23
IV. Potash									
1. End of winter....	11	7	11	10	Emergence to end of winter.	11	7	11	10
2. Beginning of stalk growth.....	45	49	43	46	End of winter to beginning of stalk growth.....	34	42	32	36
3. Blossoming.....	94	95	95	95	Beginning of stalk growth to blossoming.....	49	46	52	49
4. Maturity.....	100	100	100	100	Blossoming to maturity....	6	5	5	5
V. Lime									
1. End of winter....	12	7	13	11	Emergence to end of winter.	12	7	13	11
2. Beginning of stalk growth.....	37	29	34	34	End of winter to beginning of stalk growth.....	25	22	21	23
3. Blossoming.....	88	88	94	90	Beginning of stalk growth to blossoming.....	51	59	60	56
4. Maturity.....	100	100	100	100	Blossoming to maturity....	12	12	6	10
VI. Magnesia									
1. End of winter....	4	9	6	6	Emergence to end of winter.	4	9	6	6
2. Beginning of stalk growth.....	24	32	18	25	End of winter to beginning of stalk growth.....	20	23	12	19
3. Blossoming.....	67	91	98	85	Beginning of stalk growth to blossoming.....	43	59	80	60
4. Maturity.....	100	100	100	100	Blossoming to maturity....	33	10	3	15

also to winter barley and wheat, the behavior of which is disclosed by the averages given in table 2. These have been compiled from rather heterogeneous figures, and variations among them are less than those within the

TABLE 3

Growth and nutrient absorption of small grains, potatoes, peas, and winter rape

PLANT	PERIOD OF GROWTH	PER CENT OF MAXIMUM FORMED OR ABSORBED		REMARKS
		Dry matter	Nutriment	
I. Small grains	1. Emergence to beginning of stalk growth	20	40	See text under this subject.
	2. Beginning of stalk growth to blossoming	60	50	
	3. Blossoming to maturity	20	10	
II. Potatoes	1. Emergence to beginning of blossoming	25	50	See text under this subject.
	2. Beginning of blossoming to beginning of leaf yellowing	75	50	
	3. Beginning of leaf yellowing to maturity	0*	0*	
III. Peas (Early Viktoria)	1. 14 days before beginning of blossoming	10	15	Growth rather uniform; duration of blossoming, 2 weeks, little secondary growth. Cessation of nutrient absorption about 10 days before maturity.
	2. From 1 to beginning of blossoming	30	65	
	3. From 2 to end of blossoming	40	15	
	4. From 3 to maturity	20	5	
IV. Winter rape	1. To beginning of winter	20	40	Emergence beginning September. Normal fall growth; no complete cessation of growth during mild winter.
	2. From beginning of winter to blossoming	50	50	
	3. From blossoming to 4 weeks before maturity	30	10	
	4. Pod formation to maturity (comprising about 4 weeks)	0*	0*	

* Retrogradation by lixiviation and shedding of leaves especially of lime and potash occurring in large amounts in maturing leaves.

species. Winter grains thus form a group with respect to nutrient absorption. Typical values for them are given in the last column of table 2 and are reduced to a few summarized values in table 3, I. The rounding of the absorption figures in the summary (Table 3, I), the grouping of all soil nutrients as "nu-

triment," and the omission of the data for late winter are based on the following considerations:

Rounding is intended to prevent any illusion as to the exactness of the figures and clearly to show their character as roughly supporting data.

Although uncertain, for the present at least it may be considered that the individual soil nutrients do not exhibit deviations from the total absorption.

The late winter given as the time of the first period in tables 1 and 2 does not occur at any particular period of growth and may not logically be adduced as a point of development.

Numerous references indicate that what was said for grains applies also to other plants. Since in a small space it is impossible exhaustively to evaluate the pertinent observations, only a few examples will be adduced as proof. With spring barley, oats, and wheat, the relationships are so very simple that they easily fit into the arrangement given in table 3, I. The potato, the development of which extends over varying lengths of time according to variety and is difficultly divided into sharply differentiated periods, differs considerably from the grains. The author sought to differentiate as well as possible the points of development given in table 3, II, on the basis of numerous references available to him, hoping that in this way he approached actuality. To round out the picture, peas and winter rape are given in table 3, III and IV, as examples of seed legumes and winter oleaginous crops. Unfortunately, in the case of these, it was necessary to rely only on a few individual experiments, which naturally limits the applicability of the values given. In this connection, however, small variations are of no significance, since our norms, by origin, are only arithmetical averages around which the individual cases tend to group themselves more or less as single values around the respective mean. Pending further details given the summary of this section, it may be stated here that the nutrient absorption becomes a component characteristic to some extent in the general scheme of development of the plant species, which certainly would appear more clearly if, in the experiments, only homogeneous plants had been employed.

Seasonal absorption of nutrients

Since nutrient absorption of the plants is correlated with their development, which, in turn, is correlated with the season, it follows that there is a relationship between nutrient absorption and season. The calendar as a determining basis, however, has only local validity because specific periods of development fall on quite different dates, according to geographic and climatic conditions of the location; and fixed points in development, which must be ignored if periods of absorption are divided on a calendar basis, vary considerably from year to year. A calendar basis, therefore, gives less stability to data on nutrient needs than does the adaptation of the data to the general pattern of development. Only by exact indentification of the stage of development on the day of the observation do determinations on the course of nutrient ab-

sorption contribute to the solution of the problem as a whole. From statements in the reports at hand, this frequently does not seem to be sufficiently recognized.

For the practical use of fertilizers, however, recommendations for certain weeks or months are properly popular. From data at hand we have, therefore, made comparative calculations of the nutrient needs for various periods of development and of season and, based on the data in table 4, summarized these results in tables 5 and 6.

TABLE 4

Course of growth of various plants

I. SMALL GRAINS	DATE OF					DAYS BETWEEN					
	1 Seeding	2 Emergence	3 Beginning of stalk growth	4 Blossoming	5 Maturity	1 and 2	2 and 3	3 and 4	4 and 5	1 and 5	2 and 5
1. Winter barley	9–15	9–25	4–17	5–19	6–30	10	204	32	42	288	278
2. Winter rye	9–25	10–5	4–9	5–25	7–14	10	186	46	50	292	282
3. Winter wheat	10–1	10–11	4–21	6–6	7–22	10	193	46	46	295	285
4. Summer barley (Hanna type)	4–1	4–10	5–12	6–11	7–15	9	32	30	34	105	96
II. POTATOES	**DATE OF**					**DAYS BETWEEN**					
	1 Planting	2 Emergence	3 Beginning of blossoming	4 First yellowing of foliage	5 Maturity	1 and 2	2 and 3	3 and 4	4 and 5	1 and 5	2 and 5
5. Very early (Erstling type with presprouting)	3–20	4–10	5–20	6–25	7–10	21	40	36	15	112	91
6. Early (July type without presprouting)	4–10	5–10	6–23	7–29	8–15	30	44	36	17	127	97
7. Medium-early (Johannssen type)	4–15	5–15	7–5	8–15	9–15	30	51	41	31	153	123
8. Medium-late (Industrial type)	4–20	5–20	7–15	9–5	10–15	30	56	52	45	183	153

The dependent relationship between nutrient absorption and development is evident also in a varying duration in nutrient absorption, which tends to correspond roughly with duration of growth. Table 4 gives some examples of this. Even in the narrow compass of Germany the dates of the periods of growth vary by weeks or even months, as a result of climatic conditions of the locality and seasonal weather. The data of table 4 are applicable to other

TABLE 5

Nutrient absorption correlated with periods of growth

PERIOD	LENGTH OF PERIOD	ABSORPTION FOR PERIOD		
		Nitrogen	Phosphoric Acid	Potash
I. Winter barley				
	*days**	*kgm./ha.*	*kgm./ha.*	*kgm./ha.*
1. Emergence to beginning of stalk growth	204	35.4	16.7	34.6
2. Beginning of stalk growth to blossoming	32	44.2	20.8	43.2
3. Blossoming to maturity	42	8.8	4.2	8.6
Total growing period	278	88.4	41.7	86.4
II. Winter rye				
1. Emergence to beginning of stalk growth	186	36.9	18.8	41.3
2. Beginning of stalk growth to blossoming	46	46.2	23.4	51.6
3. Blossoming to maturity	50	9.2	4.7	10.3
Total growing period	282	92.3	46.9	103.2
III. Winter wheat				
1. Emergence to beginning of stalk growth	193	37.5	17.9	36.2
2. Beginning of stalk growth to blossoming	46	46.8	22.4	45.2
3. Blossoming to maturity	46	9.4	4.5	9.0
Total growing period	285	93.7	44.8	90.4
IV. Summer barley (Hanna type)				
1. Emergence to beginning of stalk growth	32	30.4	15.8	29.0
2. Beginning of stalk growth to blossoming	30	38.1	19.7	36.3
3. Blossoming to maturity	34	7.6	3.9	7.2
Total growing period	96	76.1	39.4	72.5
V. Potatoes—very early with presprouting				
1. Emergence to beginning of blossoming	40	37.5	12.5	47.0
2. Beginning of blossoming to beginning of yellowing of foliage	36	112.5	37.5	141.0
3. Beginning of yellowing of foliage to maturity	15	0	0	0
Total growing period	91	150.0	50.0	188.0
VI. Potatoes—early without presprouting				
1. Emergence to beginning of blossoming	44	37.5	12.5	47.0
2. Beginning of blossoming to beginning of yellowing of foliage	36	112.5	37.5	141.0
3. Beginning of yellowing of foliage to maturity	17	0	0	0
Total growing period	97	150.0	50.0	188.0

* From table 4.

TABLE 5—*Concluded*

PERIOD	LENGTH OF PERIOD	ABSORPTION FOR PERIOD		
		Nitrogen	Phosphoric Acid	Potash
VII. Potatoes—medium-early				
	*days**	*kgm./ha.*	*kgm./ha.*	*kgm./ha.*
1. Emergence to beginning of blossoming	51	45.0	15.0	56.3
2. Beginning of blossoming to beginning of yellowing of foliage	41	135.0	45.0	168.7
3. Beginning of yellowing of foliage to maturity	31	0	0	0
Total growing period	123	180.0	60.0	225.0
VIII. Potatoes—medium-late				
1. Emergence to beginning of blossoming	56	49.5	16.5	62.0
2. Beginning of blossoming to beginning of yellowing of foliage	52	148.5	49.5	186.0
3. Beginning of yellowing to maturity	45	0	0	0
Total growing period	153	198.0	66.0	248.0

districts only after appropriate modifications in the dates. The evaluation of the table is reserved for the summary of this section.

Nutrient absorption as influenced by ecological factors

In the ecology of the plant, external growth factors arising from weather, soil, and the living world surrounding the plant all exert an important physiological effect. That this effect extends to the course of nutrient absorption is self-evident because of its close relationship to growth. The analysis of the form and distribution of the active influences would require much space and would only impair the clarity of this study. We shall content ourselves, therefore, with passing references to these influences and shall consider now the matter of nutrient supply, which is particularly important in this connection.

The available observations offer sufficient evidence that nutrient supply is a determining factor in nutrient absorption and growth and in the relationships between them. It is an ecological phenomenon if plants, within certain limits determined by inherent factors, temporarily absorb, from an abundant supply of readily absorbable nutrients, more than the normal needs, for the purpose of future elaboration; or attempt to recover as much ground as possible from a belatedly supplied nutriment, following an initially scanty supply.

A marked temporary storing of absorbed nutriment, however, is always accompanied by modifications in growth. These are slight in the case of an absorption of phosphoric acid and potash well in advance of physiological

TABLE 6

Nutrient absorption correlated with calendar periods

PERIOD*	PER CENT OF HIGHEST AMOUNT		FORMED OR ABSORBED PER MONTH		
	Dry matter	Nutriment	Nitrogen	Phosphoric Acid	Potash
I. Winter barley					
			kgm./ha.	*kgm./ha.*	*kgm./ha.*
1. To March 31	12	25	22.1	10.4	21.6
2. April	32	35	31.0	14.6	30.3
3. May	42	35	30.9	14.6	30.2
4. June	14	5	4.4	2.1	4.3
Total period of growth	100	100	88.4	41.7	86.4
II. Winter rye					
1. To March 31	16	33	30.5	15.4	34.1
2. April	31	30	27.7	14.1	31.0
3. May	40	31	28.6	14.5	32.0
4. June	9	4	3.7	1.9	4.1
5. July	4	2	1.8	0.8	2.0
Total	100	100	92.3	46.9	103.2
III. Winter wheat					
1. To March 31	13	24	22.4	10.8	21.7
2. April	19	26	24.4	11.6	23.5
3. May	42	34	31.9	15.2	30.7
4. June	20	14	13.1	6.3	12.7
5. July	6	2	1.9	0.9	1.8
Total	100	100	93.7	44.8	90.4
IV. Summer barley					
1. April	11	23	17.5	9.1	16.7
2. May	45	47	35.8	18.5	34.1
3. June	40	28	21.3	11.0	20.3
4. July	4	2	1.5	0.8	1.4
Total	100	100	76.1	39.4	72.5
V. Potatoes—very early with presprouting					
1. April	7	18	27.0	9.0	33.9
2. May	43	49	73.5	24.5	92.1
3. June	50	33	49.5	16.5	62.0
Total	100	100	150.0	50.0	188.0
VI. Potatoes—early without presprouting					
1. May	8	22	33.0	11.0	41.4
2. June	33	40	60.0	20.0	75.2
3. July	59	38	57.0	19.0	71.4
Total	100	100	150.0	50.0	188.0

* See table 5 for duration.

TABLE 6—*Concluded*

PERIOD*	PER CENT OF HIGHEST AMOUNT		FORMED OR ABSORBED PER MONTH		
	Dry matter	Nutriment	Nitrogen	Phosphoric acid	Potash
VII. Potatoes—medium-early					
			kgm./ha.	*kgm./ha.*	*kgm./ha.*
1. May	5	14	25.2	8.4	31.5
2. June	18	31	55.8	18.6	69.7
3. July	59	45	81.0	27.0	101.3
4. August	18	10	18.0	6.0	22.5
Total	100	100	180.0	60.0	225.0
VIII. Potatoes—medium-late					
1. May	3	7	13.9	4.6	17.4
2. June	11	23	45.5	15.2	57.0
3. July	39	40	79.2	26.4	99.2
4. August	44	28	55.4	18.5	69.4
5. September	3	2	4.0	1.3	5.0
Total	100	100	198.0	66.0	248.0

needs. Neither of these nutrients has a forcing action, and through absorption in the soil both are largely protected against leaching and the formation of solutions of such concentration as to be physiologically injurious. Excessive early nourishment with nitrogen has a more noticeable influence. Apart from the fact that the portion of this nutrient that is not quickly absorbed may easily be lost, the young plants with excess nitrogen are likely to make a rapid and tender growth accompanied by decreased resistance to drought, frost, lodging, and parasites.

Even more undesirable are the results of a delayed supply of plant nutrients. Special pot experiments, partial results of which are given in table 7, indicate that delayed application is much less detrimental to the absorption of nutrients than to the effect on yield. Absorbed nutrients that are not transposed into yield are lost for all practical purposes if, from the increased content, there is no compensatory improvement in quality. This really is a factor only in the case of nitrogen. Secondary growth also is a factor arising out of the absorption of a belatedly supplied nutriment. This growth does not reach maturity and, at least in the case of plants utilized at maturity, is practically valueless or even deleterious because of interference with harvesting. The formation of late shoots is essentially a biological expedient for the purpose of prolonging the ability of the plant to react to the improved growing conditions occurring in the later period of growth. The relative absorption of a delayed

TABLE 7

Pot experiments with oats

TIME OF APPLICATION	EARLY	MEDIUM-EARLY	LATE	DIVIDED
First application	At seeding	At emergence	At beginning of stalk growth	At seeding
Second application	At beginning of stalk growth	At beginning of stalk growth	At beginning of blossoming	At heading time
I. Nitrogen				
1. Dry matter, in gm. produced by 1 gm. nitrogen fe.tilizer				
Grain	42	39	12	36
Straw and roots	77	64	47	66
2. Per cent of nitrogen in dry matter				
Grain	1.41	1.57	2.10	1.54
Straw	0.38	0.35	0.66	0.37
3. Per cent of nitrogen utilized	94	91	87	90
4. Stalks per plant at maturity				
Mature	2.5	2.0	1.2	2.0
Immature	0	0	1.1	0
II. Phosphoric acid				
1. Dry matter, in gm. produced by 1 gm. phosphoric acid fertilizer				
Grain	84	82	4	81
Straw and roots	119	100	69	105
2. Per cent of phosphoric acid utilized	52	62	63	67
3. Stalks per plant at maturity				
Mature	3.3	3.5	1.5	3.5
Immature	0	0	1.7	0
III. Potash				
1. Dry matter, in gm. produced by 1 gm. potash				
Grain	22	23	9	22
Straw and roots	39	33	5	31
2. Per cent of potash utilized	94	96	90	93
3. Stalks per plant at maturity				
Mature	3.1	3.5	3.3	3.5

fertilization by normal and secondary shoots of the same plant is shown, as an example, in the following results of a special plot experiment with oats:

NUTRIENT	PERCENTAGE OF THE BELATEDLY ABSORBED FERTILIZER	
	In normally growing and maturing stalks	In secondary stalks immature at harvesting
Nitrogen	58	42
Phosphoric acid	61	39

The yield from the late fertilization was affected only to the extent that valueless second growth increased the difficulty of harvesting.

The more favorable the nutrient supply in the early period of development of the plant, the greater is the absorption in advance of needs, within certain limits determined by inherent characteristics of the plants. The statements for nutrients as a whole hold, more or less, also for the individual nutrients present in the plants. That the absorption of these nutrients proceeds at varying rates according to their physiological function is obviously probable and almost certain, as judged from observations on the physiological activation of the substances dormant in the embryo. The numerous reports on the course of nutrient absorption available to the author, however, show only that absorption of the primary nutrients in greater or lesser degree always precedes growth, and that sometimes one, sometimes another, nutrient is in the lead. Nitrogen frequently is in the lead in nutrient absorption, but it can be reduced to second or third place if another material is copiously supplied. The conception that the availability at a particular time definitely influences the relative absorption of the individual nutrients may be considered as correct in the light of present-day knowledge.

Can nutrient absorption during development show also a cessation or retrogradation? In reports of work at hand, zigzag curves for absorption are very common. These are especially frequent toward the end of growth, indicating that the regression is traceable to replacement of leached or decayed plant parts by subsequent regeneration. In spite of this, the regression can not be ascribed entirely to experimental error or to loss or leaching of necrotic plant tissue. Recent observations on cuticular secretion show rather clearly that the living leaves also continually "sweat." Considerable quantities of nutrients thus are washed off by rain and returned to the soil. The periodic variation in the nutrient content of the plant is thus the difference between absorption and return to the soil A retrogradation of absorption curve indicates a predominance of the latter.

An indirect influence of weather on nutrient absorption is plainly shown by the great influence of weather on the development of plants. The relationships between weather and nutrient absorption, however, certainly are not limited to this. The common assumption that, in dry weather, crops are low in phosphoric acid but high in protein is a tacit admission that drought shifts the relationships among anabolism, nitrogen absorption, and phosphoric acid absorption in favor of nitrogen and at the expense of phosphoric acid. Küpper, to whom the author more than 10 years ago assigned the reexamination of this subject as a doctorate problem (1), believed that he had shown that increasing soil moisture, up to a certain optimum, favored an earlier absorption of all nutrients, whereas dryness of soil had an opposite effect and disturbed absorption relationships to the disadvantage of phosphoric acid, at least until the late stages of development. The relationships between weather and nutrient absorption cannot, in any sense, be considered as exhausted by these

findings. The supporting facts available to the author, however, are not sufficient to warrant the drawing of any further conclusions.

That attacks by parasites affect the nutrition of the plant, and thereby can disturb the normal absorption of nutrients, may be considered as proved. The trend of the influence of the attack is so little known that a discussion at present appears useless. It may be considered as certain, however, that a heavy attack of nematodes, Phytophthora, and many other diseases so critically impairs nutrient absorption, along with growth, that studies on badly diseased plants give no conception at all of the normal course of absorption.

Summary

How much Liebscher's theory needed correction may be shown by a comparison of the thesis set forth in the section "Liebscher's teachings" with the following facts:

The physiological characteristics of the species, as well as its environment during growth, have an influence on nutrient absorption. It is not possible, therefore, to speak of a strictly characteristic course of nutrient absorption.

Since nutrient absorption, however, is closely related to the broadly characteristic course of development, there are at least indirect relationships between species and nutrient absorption. The course of nutrient absorption is just as typical as is the development of the plant. Modifications in both arise from internal variabilities of varieties and sports within one species of plants, as well as from their environment during growth.

It is characteristic of the relationships between anabolism and nutrient absorption that the absorption of soil nutrients at first markedly precedes synthesis. Later, a gradual equilibration and, after a high point of development is passed, a reversal of the relationship occur. The author has never observed plants which reached the stage of cessation of synthesis before that of cessation of nutrient absorption. Plants having secondary growth, however, may easily deceptively appear to be an exception.

Nutrient absorption and synthesis end some time before the seed is ripe. In many plants this time interval is masked by secondary growth.

The interrelationships within the general field of development, just as much as growth itself, determine nutrient absorption, dependent, of course, also on duration and seasonal conditions.

None of these relationships, however, are rigid, for all of them are subject to ecological vicissitudes. These are manifested in a storing of nutriment above immediate needs by the plants at a time of plentiful supply. This utilization of supply is closely adjusted to the growth of the plant.

An absorption of phosphoric acid and potash in early growth in advance of physiological need is not deleterious, since these nutrients are not stimulating. On account of soil absorption, they are protected against leaching, and furthermore, they cannot cause an increase in the concentration of the soil solution sufficient to be injurious to the plant. Excessive nutriment in early growth can really be dangerous only in a case of nitrogen. The portion of this nutrient that is not quickly absorbed may be lost, and that absorbed above immediate needs may reduce the resistance of the tender, succulent plants to parasites, frost, and drought.

The plant seeks to obtain the greatest possible advantage from the belatedly absorbed nutriment. Storage in senescent organs and rejuvenation of the plant are ways in which this is done. Potatoes, Betae, Brassicae, and Dauci, for example, rejuvenate themselves mainly by turning green again and forming new leaves. With the Gramineae, Papilionaceae, and Cruciferae the rejuvenation takes the form mostly of suckering. The delayed maturity

resulting from the rejuvenation and increased growth arising from a belated fertilization are undesirable characteristics from the viewpoint of farming.

The delayed supplying of nutriment is much more unfavorable to the efficacy of the nutrient than to its absorption. For example, the stalks of the grains can still store nutrients during late growth without increasing in weight. From a practical standpoint, it is naturally undesirable to have an increase in content without an increase in quality.

The portion of the delayed fertilization used in the formation of secondary growth, likewise serves little or no practical end, since this growth tends to be of little value and, under many circumstances, increases the difficulty of harvesting. Supplying the nutriment too late is, therefore, highly inadvisable.

All these statements apply primarily to nitrogen, phosphoric acid, and potash. A similar relationship for magnesium is almost certain and for lime and other soil nutrients, at least probable.

The maturing leaves usually store large amounts of lime. Although this takes place chiefly at the expense of other parts of the plant, the soil lime also occasionally appears to be involved in this supplementary storing. The physiological significance of this phenomenon does not lie within the scope of this paper.

That the height of nutrient absorption by legumes occurs during the final period of growth is not apparent and, still less, proved. In any case, the author has never succeeded in inducing this experimentally. Ununiformly developed plants probably could misleadingly indicate such behavior, and observations made on such material may also have misled Liebscher.

A marked precedence of nutrient absorption during early growth, according to Liebscher, is dependent on a greatly increased supply of nutrients. That certainly would be correct if there were any characteristically defined precedence of the absorption of nutrients at all. The available observations indicate this often enough. If the individual observations are examined further, however, it will be seen that variations within a species are greater than those between the species. It is almost certain that the relationships between available nutrients and other growth factors more than the class of plant determine the degree of precedence of nutrient absorption.

The absorption of the individual nutrients, in fulfilling their physiological functions, also may reach the end point with varying rapidity. The work bearing on this point does not, however, show to what extent this behavior is dependent on nutrient and species. It has been repeatedly shown that the relative availability of the individual nutrients definitely influences their absorption relationships during the entire growth.

Nutrient absorption can also be negative temporarily. This is explained by the differential character of the periodic changes. According to the relationship of the absorbed nutrients and of those returned to the soil from the epidermis and roots of the plant, the net result may be positive or negative, and the total trend, accordingly, progressive or retrogressive.

Investigations on the course of nutrient absorption permit a deeper insight into the problem only when the plants being investigated are of equal development and health; when conditions for easy and certain differentiation of points of development of the plant as fixed bases are introduced into the investigation; when characteristic behavior is not deduced from one case but from a sufficient number of dependable observations. In this respect, previous work leaves much to be desired and therefore cannot be utilized in the development of a basically sound theory for the problem.

THE EFFICIENT AND PRACTICAL USE OF FERTILIZERS

General

The data on nutrient requirements given in tables 8 to 10 apply to high yields of average content and include the nutrients contained in the roots and

TABLE 8

Nutrient absorption by calendar periods

I. Basic data for absorption calculations

PLANT	YIELD	REMOVAL*, IN KGM./HA.			DURATION OF GROWTH IN DAYS (ROUNDED)	DURATION OF NUTRIENT ABSORPTION IN DAYS (INCLUDING WINTER)
		Nitrogen	Phosphoric acid	Potash		
Winter rye	36 grains	92	47	103	280	270
Summer barley	34 grains	76	39	73	100	90
Very early potatoes	250 tubers	150	50	188	90	80
Medium-late potatoes	330 tubers	198	66	248	150	140
Sugar beets	400 beets	200	70	290	170	160
Winter rape	25 grains	194	89	164	310	280
Peas (Viktoria)	30 grains	160	50	110	100	90

II. Absorption data, in kgm/ha.

PLANTS	FALL TO 11–30	WINTER, 12–1 TO 2–28	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER
1. Nitrogen									
Winter rye	7.4	2.8	21.0	27.7	28.6	3.7	1.8	....	....
Summer barley	....	...	....	17.5	35.8	21.3	1.5	....	....
Very early potatoes	....	...	....	27.0	73.5	49.5	....	....	....
Medium-late potatoes	....	...	....	....	13.9	45.5	79.2	55.4	4.0
Sugar beets	....	...	....	....	12.0	40.0	78.0	50.0	20.0
Winter rape	77.6	9.7	42.7	44.6	19.4	....	....	....	....
Peas (Viktoria)	....	...	....	4.8	52.8	92.8	9.6	....	....
2. Phosphoric acid									
Winter rye	3.8	1.4	10.5	14.1	14.5	1.9	0.8	....	....
Summer barley	....	...	....	9.1	18.5	11.0	0.8	....	....
Very early potatoes	....	...	....	9.0	24.5	16.5	....	....	....
Medium-late potatoes	....	...	....	....	4.6	15.2	26.4	18.5	1.3
Sugar beets	....	...	....	....	3.5	10.9	21.0	19.6	14.0
Winter rape	35.6	4.5	19.6	20.4	8.9	....	....	....	....
Peas (Viktoria)	....	...	....	1.8	17.0	25.8	1.4	....	....
3. Potash									
Winter rye	8.2	3.1	22.6	31.0	32.0	4.1	2.0	....	....
Summer barley	....	...	....	16.7	34.1	20.3	1.4	....	....
Very early potatoes	....	...	....	33.9	92.1	62.0	....	....	....
Medium-late potatoes	....	...	....	....	17.4	57.0	99.2	69.4	5.0
Sugar beets	....	...	....	....	14.5	49.3	87.0	87.0	52.2
Winter rape	65.6	8.2	36.1	37.7	16.4	....	....	....	....
Peas (Viktoria)	....	....	....	5.5	40.7	60.5	....	....	....

* Including roots and crop residue.

crop residues. Attention is directed to the fact that the data represent arithmetic averages and, therefore, are approximations.

The tables give the monthly and daily needs of the plants in various growth and calendar periods. They thus support the suggestions in the latter part of this section, under "Special Considerations for Some Plant Groups." In order to facilitate summarization, the plants are divided into two contrasting

TABLE 9

*Daily absorption divided on basis of periods of growth**

PLANT	AVERAGE DAILY ABSORPTION IN GM./HA. DURING GROWTH PERIOD											
	Nitrogen				Phosphoric acid				Potash			
	1	2	3	1-3	1	2	3	1-3	1	2	3	1-3
Small grains:												
I. Winter barley	174	1,381	210	318	82	650	100	150	170	1,350	205	311
II. Winter rye	198	1,004	184	327	101	509	94	166	222	1,122	206	366
III. Winter wheat	194	1,018	204	329	93	487	98	157	188	983	196	317
IV. Summer barley	950	1,270	224	792	494	657	115	410	906	1,210	212	755
Potatoes:												
V. Very early with pre-sprouting	938	3,125	0	1,648	312	1,042	0	550	1,175	3,917	0	2,066
VI. Early without pre-sprouting	852	3,125	0	1,546	284	1,042	0	515	1,068	3,917	0	1,938
VII. Medium-early	882	3,293	0	1,463	294	1,097	0	488	1,104	4,115	0	1,829
VIII. Medium-late	884	2,856	0	1,294	295	952	0	431	1,107	3,577	0	1,621

* Description of periods of growth (see table 5 for days in each period).

PERIOD	SMALL GRAINS	POTATOES
1	Emergence to beginning of stalk growth	Emergence to beginning of blossoming
2	Beginning of stalk growth to blossoming	Beginning of blossoming to beginning of yellowing of foliage
3	Blossoming to maturity	Beginning of yellowing of foliage to maturity

groups containing all the related transition types, according to their absorption of nutrients. The members of these groups are characterized as follows:

1. Nutrient absorption extending over a relatively short time with a distinct point of maximum requirement during the period of greatest absorption, occurring at a time when the soil is rather dormant and the roots of the plant are poorly developed.
2. Nutrient absorption extending over a longer period of time with less distinct point of maximum need; the period of greatest absorption occurring at a time of greater activity in the soil and of better root development.

Plants in intermediate positions between the groups occur as a result of the arbitrary and gradually changing development of the criteria presented for the groups.

Plants in group 1 do best on soils already in a fertile state and/or supplied with quickly acting fertilizers. Slowly acting fertilizer materials should be used only when they are applied soon enough so that they already will have

TABLE 10

*Daily absorption divided by calendar periods**

PERIOD	AVERAGE DAILY ABSORPTION							
					Potatoes			
	Winter barley	Winter rye	Winter wheat	Summer barley	Very early with pre-sprouting	Early without pre-sprouting	Medium early	Medium late
I. Nitrogen								
	gm./ha.	*gm./ha.*	*gm./ha.*	*gm./ha.*	*gm./ha.*	*gm./ha.*	*gm./ha.*	*gm./ha.*
Emergence to March 31†	228	328	273	.....	.....	.....	.....	.....
April	1,033	923	815	583	900	.....	.....	.....
May	997	923	1,029	1,155	2,371	1,064	813	448
June	147	123	437	710	1,650	2,000	1,860	1,517
July	.....	58	61	48	.....	1,839	2,613	2,555
August	.....	.....	.....	.....	.....	.....	.....	1,787
September	.....	.....	.....	.....	.....	.....	.....	133
II. Phosphoric acid								
Emergence to March 31	107	166	132	.....	.....	.....	.....	.....
April	487	470	387	303	300	.....	.....	.....
May	471	468	490	597	790	355	274	148
June	70	63	210	367	550	667	620	507
July	.....	26	29	26	.....	613	871	852
August	.....	.....	.....	.....	.....	.....	194	597
September	.....	.....	.....	.....	.....	.....	.....	43
III. Potash								
Emergence to March 31	223	367	265	.....	.....	.....	.....	.....
April	1,010	1,033	783	583	1,130	.....	.....	.....
May	974	1,032	990	1,155	2,971	1,335	1,016	561
June	143	137	423	710	2,067	2,507	2,323	1,900
July	.....	65	58	48	.....	2,303	3,268	3,200
August	.....	.....	.....	.....	.....	.....	726	2,239
September	.....	.....	.....	.....	.....	.....	.....	167

* See table 6.

† 90 days for barley, 85 days for rye and wheat, deducted from the total time for winter dormancy.

been assimilated by the soil and be in an available condition at the period of greatest nutrient absorption by plants.

Plants in group 2, on the other hand, can utilize the less readily available soil nutrients and the slowly acting fertilizers. When quickly acting mate-

rials are applied, the applications should be correlated with the course of nutrient absorption.

These statements apply fundamentally to all nutrients. If in the latter part of this section more attention is paid to nitrogen than to phosphoric acid and potash, this is due to their different behavior in the soil. Soil absorption exerts a marked regulating effect on the activity of phosphoric acid and potash. The course of absorption of these nutrients, however, requires attention, to the extent that in exceptional cases one must determine how late fertilization with phosphoric acid and potash is advisable. Ordinarily the supply of these nutrients for the plants must be assured by an appropriate fertilizer application before or at the time of seeding. In view of its general applicability, this postulation is emphasized at this time and is not repeated with each of the plants. In contrast with its effect on phosphoric acid and potash, soil absorption exerts very little regulating effect on the action of nitrogen, with the exception of the nitrogen in some slowly acting organic fertilizers. The time of application and the period of activity are therefore much closer together. For this reason it is advisable to correlate as closely as possible the time of nitrogen fertilization with the distribution of the requirements of the plants being grown.

In order to avoid erroneous conclusions, one should always keep in mind that there is an interval between the application of fertilizers and the initiation of their action. Since the duration of this interval cannot by any means be generalized, we must content ourselves with the broad statement that the interval varying from days to years, is shortened by increased solubility of the fertilizer, retention of solubility after the fertilizer comes in contact with the soil, absorbability by the plant without time-consuming changes in form, high chemical and biological activity in the soil, damp heat, and great assimilative capacity of the fertilized plant.

Special considerations for some plant groups

For greater clarity, plants with similar courses of nutrient absorption are arranged in groups, and the brief discussion is limited to especially important representative plants in each group. The basic data for the discussions are to be found in tables 8 to 10.

1. *Fall-sown grains* are typical of plants absorbing nutrients in autumn. The amount of absorption at this time is closely related to fall growth and is therefore dependent on the time of emergence and on fall growing conditions. At the most, 10 per cent of the total nutrient removal may be assigned to the period preceding winter. Late seedings coming up during or after winter make up for lost time in early spring. In severe winters, absorption is at a standstill; in mild winters it never completely ceases, but, even then, the cold season makes a well-defined period in development and nutrition. Only the warm spring sun arouses activity again in both. The maximum point in nutrient absorption occurs during the period of rapid stalk growth. There-

after, from the beginning of blossoming a progressive decrease occurs, absorption ceasing altogether some weeks before maturity. Nutrient absorption extends over 270 to 280 days, including the winter months, of which about 120 days normally fall in the period following winter. If differences due to variation in time of seeding are eliminated, winter barley and wheat are similar in nutrient requirements and absorption to rye, selected as representative of this group of plants in table 10. The small variations occurring with normal seeding and harvesting times can be seen in tables 8 and 9.

The course of nutrient absorption by winter grain makes it appear imperative that the nitrogen be so furnished that most of it is readily available to the plant at the rapidly growing period of stalk development and can be entirely consumed by the beginning of blossoming. The nitrogen requirement before winter is so little with early seeding and even much less with late seeding that it can be met by the soil supply or a very moderate fertilizer application. The much greater need during the period of shoot development can be provided, on soils that are not too light, by applications of calcium cyanamid and slowly acting organic nitrogen fertilizers shortly before seeding or by top-dressing shortly before the end of winter. If a rather large top-dressing is necessarv to take care of the needs, either ammonia or nitrate nitrogen in several applications should be given, in view of the extended requirement curve in the period following winter.

In potash-phosphate fertilization, an early top-dressing with superphosphate, Thomasmeal, and high-grade potash salts can very well make up for a lack of fall fertilization. Top-dressings with kainit before and after winter not only serve the purpose of combating weeds but also supply potash to the plant. Barnyard and green manures are suitable for winter grains if their activity is insured at the right time and unfavorable influence on growth and soil structure is prevented.

2. With *summer grains*, nutrient absorption usually begins shortly after emergence at the end of April or the beginning of May and then passes through the same phases as winter grain with a markedly shortened duration and a more sharply defined point of maximum requirement. The short lapse of 100 days and high peak requirements characterize the nutrient absorption of summer grains. This is especially true for early maturing varieties; the maximum and end points in absorption are shifted for late varieties to correspond to their longer growth.

Short duration of absorption, rapid increase in requirement, and marked point of maximum requirement of summer grains indicate the necessity of a quickly available supply of nutriment. This must be assured by a fertile soil and by quickly acting fertilizers, used, at the latest, when the soil is being prepared. Top-dressing is only an expedient, since its action even with ready availability and early application is dependent on the occurrence of rain necessary for dissolving it. Barnyard manure, green manure, and all slowly acting fertilizers thus promise results on summer grains only when they are so used

that they have become assimilated into the soil, at the latest, by the beginning of tillering.

3. *Winter rape* is unusual in that it has two periods of high requirements, shortly before and after the winter season. These peak requirements, combined with the general high level of nutrient needs of this crop, indicate the necessity of a soil in good fertile condition or a fertilization with such materials as will be in an available condition for the plant, at the latest, at the time of the peak requirement preceding winter. For these reasons, manure, correctly applied at the right time, is excellent for rape. An application of calcium cyanamid before seeding supplements very well the nitrogen in the manure. Whether another top-dressing in late winter is necessary to take care of the peak requirement after the winter season depends entirely on the fertility condition of the soil and fall fertilization. When these are not sufficient to fill the needs, a top-dressing with ammonia or nitrate nitrogen is necessary immediately following winter. Naturally, the large amounts of nitrogen necessary for rape will be efficiently utilized by the crop only if a sufficient supply of phosphoric acid and potash is provided.

Winter rapeseed is comparable to winter rape in its course of nutrient absorption, but the nutrient needs of the rapeseed are 20 to 30 per cent less than those of the rape, corresponding to the lower levels of yield, and the requirements of the more quickly developing plants must be supplied within a shorter period of time and closer to the cold season of the year. These two later factors make it more difficult to provide the requirements and necessitate a quickly available supply of nutrients.

4. The *hoed crops*[3] are represented in table 8 by medium-late potatoes and sugar beets. They all have a high nutrient requirement, a principal period of absorption rather uniformly spread over the three summer months, a remarkable rise to a maximum requirement in the middle of summer, and a relatively extended absorption curve. Absorption by potatoes of normal maturity ceases the last of August or the first of September, and by sugar beets about a month later, lasting thus 120 and 150 days respectively. The normal cessation of absorption is disturbed commonly by Phytophthora attacks on potatoes and not uncommonly by drought and various leaf diseases on sugar beets.

The field varieties of beets, rutabagas, and carrots, as well as the late varieties of the cultivated garden brassicaceous plants (*Brassica oleracea varietas acephala, capitata, bullata, gemmifera, botrytis*, and *gongylodes*), are similar to sugar beets and late potatoes except that amount, principal period, and end of nutrient absorption may be shifted materially toward the winter.

It is very significant in the fertilization of all these plants that in addition to their great nutrient needs, the plants require the nutrients at about the

[3] The classification "Hackfrüchte" (literally, hoed crops) is used in Germany to include the brassicaceous along with the tuber and root crops.

same time that these become available in the soil from properly applied barnyard and green manures. Such manures must ordinarily be the basis of the fertilization of the hoed crops. Slow but continuously acting fertilizers serve as good substitutes and supplements of barnyard manure. It is difficult to dispense with the further use of commercial fertilizers, especially to take care of the great peak requirements of the hoed crops. The peak requirements of late potatoes, for instance, are best supplied by an ample application of a properly formulated fertilizer at planting time. Top-dressing with quickly acting commercial fertilizers, in addition to appropriate fertilization at or before planting, is especially suitable for beets and the cabbages, in view of their particular peak needs. That early potatoes and early cabbage must be fertilized quite differently from the late crops will be evident immediately upon examination of tables 8, 9, and 10. Winter cabbage and all other hoed crops with the principal nutrient requirement period coming toward winter are much more dependent on available fertility in the soil and on rapidly acting fertilizers than are the varieties grown in summer.

5. As representative of the *legumes grown for their seed*, the Viktoria pea, very popular in Germany for the production of mature edible peas, is given in table 8. The duration and the time of growth of its early varieties are similar to those of summer barley; its late varieties, to those of oats and spring wheat. The peas, however, are slower in their early development, which shifts nutrient absorption into the summer months. The nitrogen-fixing ability of peas is particularly advantageous in covering the great nitrogen requirements, especially since these are unusually large in June. It is the principal aim of legume fertilization to effect by suitable means a high development of this ability during the longest possible period of growth. A copious supply of potash and phosphate and appropriate liming also indirectly promote nitrogen fixation.

Great variations, however, occur in the growth and nutrient absorption of the legumes, if they actively exercise their tendency to the formation of secondary shoots. This can result in a completely new vegetative growth of the normally maturing plant by the rejuvenated shoots, with a corresponding disarrangement in nutrient absorption. Observations on such plants have given rise to reports that anabolism precedes nutrient absorption in legumes.

The other seed legumes exhibit a fundamentally similar behavior to that of peas in nutrient absorption. Considerable deviation in the amount of nutrients needed and seasonal variation in growth occur, however, which, for lack of space, cannot be gone into here.

6. For *perennial grasses and clovers, hops, asparagus, rhubarb, and other plants with overwintering root stocks*, the following behavior is typical:

During the rootstock formation, which may stretch over several years, a considerable part of the nutrients is utilized by the rootstocks.

During the following years the reserves of assimilated substances and nutriment in the rootstock are drawn upon in spring for the formation of aerial shoots. These reserves are replenished in fall.

The process of alternate spring impoverishment and fall replenishment of the rootstocks of perennial plants is repeated until their death.

Since a well-developed and replenished rootstock is very important for a firm footing and for the whole later development of the perennial plant, the fertilization, above all, must aim at a good rootstock formation and replenishment. The assimilating aerial organs furnish the means for this. Everything that promotes the healthy and vigorous development of these organs is beneficial to the rootstock and thereby to the following year's crop. The crop must therefore be provided for in the preceding summer. Among the means of accomplishing this is the ample supply of nutriment before and during summer. Within a suitable nutrient ratio the form in which the nutrients are supplied is of less importance than the sufficiency of the quantity. It is to be noted in passing that, in addition, the replenishment of the rootstocks should not be impaired by too late cutting of perennial forage crops or by too long a spring harvesting period of asparagus, rhubarb, and similar vegetables.

7. *Head lettuce, endive, spinach, spurry, white mustard, and a series of similar short-lived table and forage crops* have a duration of nutrient absorption corresponding to the short time of development. In addition, growing and harvesting of these crops may be shifted to various seasons, and the harvesting can or must be done long before maturity of seed. The rapid development and short duration of nutrient absorption require readily available fertility in the soil or quickly acting fertilizers. This is more than ever the case when, on account of early or late growing, the nutrient absorption of these plants takes place near the winter months, a time unfavorable for accumulation of nutrients.

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AN EVALUATION OF THE NEUBAUER AND THE CUNNINGHAMELLA AND ASPERGILLUS NIGER METHODS FOR THE DETERMINATION OF THE FERTILIZER NEEDS OF A SOIL

C. A. MOOERS

Tennessee Agricultural Experiment Station

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The Neubauer method for the determination of the fertilizer needs of a soil consists, essentially, of growing rye seedlings and determining their up-take of phosphoric acid and potash at the end of 17 days (3). The Cunninghamella and *Aspergillus niger* methods (2, 3) are recent improvements of the biological (Fungus) methods as developed at the Wisconsin Agricultural Experiment Station. The value and the possibilities of short methods present a serious question to agronomists. The present article is an attempt to give a practical analysis of data obtained by the Neubauer and by the Fungus methods. Reference is also made to the results from a rapid chemical test method as followed at the Indiana Station.[1]

Description of Soils Used

One hundred twenty-nine samples of soil, representing 9 distinct soil types, 1 soil type phase, and 1 land type, were used in the study. The soil types and phase, with special regard to their supplies of phosphoric acid and potash, are described briefly as follows:

Memphis silt loam, from the outset of the field plot experiments in 1909, proved to be extra well supplied with both phosphoric acid and potash. Of recent years, mild response has been noted to applications of both elements for each of a number of crops, including barley and cotton, but not definitely for corn, which, in the series on range 4 has been grown continuously in fertilizer experiments on the same plots for 26 years. During this period the entire crop, including both ear corn and stover, was removed annually. Check plot 21, receiving no fertilizer, gave an average yield for the 5 years 1931–1935 of 14.5 bushels of corn and 0.68 ton of stover per acre. Plot 22, receiving 200 pounds of superphosphate and 50 pounds of muriate of potash per acre annually, gave an average yield of 17.3 bushels of corn and 0.80 ton of stover per

[1] The Neubauer tests were made by B. W. Hatcher and J. S. Dempster under the supervision of Dr. S. F. Thornton, of the Indiana Agricultural Experiment Station (Purdue). The biological tests were made by Dr. Adolf Mehlich, of the Wisconsin Agricultural Experiment Station. All tests were carried out at the Tennessee Agricultural Experiment Station at Knoxville. The project was coöperative between the Tennessee Valley Authority and the Wisconsin and Tennessee Stations.

acre. Plot 23, receiving the same amounts of phosphate and potash as plot 29 and an annual application of 100 pounds of nitrate of soda in addition, gave an average yield of 28.9 bushels of corn and 1.29 tons of stover per acre. Plot 24, which received only the nitrate application of 100 pounds per acre, yielded an average of 32.1 bushels of corn per acre and 1.20 tons of stover per acre. On range 2, unfertilized plots produced in the last 3 of the 26 years of continuous cropping in a 3-year rotation, annual yields of nearly 2 tons of cowpea hay, 1,500 pounds of seed cotton, and 50 bushels of corn per acre.

Memphis silt loam, white-land phase, has an appreciably greater need of potash than has typical Memphis silt loam. The yield of cotton is greatly increased by the application of 50 pounds per acre of muriate of potash, which appears to meet the requirement. The yield of the clover and grass crop is increased to a less extent by a potash application; and that of corn and oats, none at all. In recent years phosphoric acid has appeared of value. This soil phase is undoubtedly of a lower order of fertility than typical Memphis silt loam.

Huntington loam is of alluvial origin and forms what is commonly known as second-bench land on Tennessee River. It is, perhaps, the best type of soil in East Tennessee and is more drouth-resistant than the uplands. The supplies of both phosphoric acid and potash are so good that even after 30 years of cropping in the experimental rotation the unmanured and unfertilized plot 1, range A, produced nearly 3 tons of cured hay per acre in 1933 and over 70 bushels of corn per acre in 1934.

Cumberland loam is a naturally fertile soil. Prior to the beginning of the field experiments in 1905, it had been in grass for many years but had suffered little loss of plant nutrients from either mowing or pasturing. During the experimental period, double cropping—cowpeas in summer and wheat in winter—has been practiced on all plots except the 7's. The cowpea crops were turned under annually on all plots except G4, G5, I4, F6, G6, and G8, where they were removed as hay. Yields for the first 20 years are reported in Bulletin 135 of the Tennessee Station. The response to phosphate was mild from the outset and has been obscured for some years by the much greater need of potash. The response to potash gradually became evident with marked deficiency in recent years of all plots not receiving potash, those where the cowpea crop was turned under annually and only the wheat crop removed, as well as those where both cowpea and wheat crops were removed.

Fullerton silt loam, an important upland type in East Tennessee, is well known to be very poor in phosphoric acid and only moderately supplied with potash. Corn in few places responds to an application of potash. On the other hand, in many places, annual legumes, such as cowpeas and soybeans for hay; truck crops; and tobacco are responsive to potash.

Decatur silt loam is naturally much more fertile than the Fullerton. In fact, Decatur uplands are rated the best in East Tennessee. Response to

phosphoric acid, however, is general. The potash supply is usually good; consequently, under livestock farming, with the careful saving and use of farmyard manure, it need not be considered. Under usual conditions, potash is not recommended for either corn or wheat but may be used to advantage for truck crops and tobacco.

Hartsells fine sandy loam is a very poor type of soil found on the Cumberland Plateau. The need of phosphate is especially pronounced. The potash supply is relatively good as far as corn, oats, and wheat are concerned, but a potash fertilizer can be used profitably in many places for hay crops and usually for potatoes.

Mericourt silt loam is named for the substation at which the samples were taken. This soil is naturally very poor in phosphoric acid and is not well supplied with potash. In general behavior it resembles Fullerton silt loam.

Montevallo silt loam is a poor type of soil derived from shale. It is especially responsive to phosphoric acid, but the supply of potash is usually rated as fair to good, or appreciably better than that of Fullerton silt loam.

Colbert silt loam, derived from clay limestone, is rather variable in natural fertility. According to the results of fertilizer experiments, the greatest need is for phosphoric acid, and little response to potash has been shown by any of the common farm crops.

Summary of Relative Standing of Soils on Basis of Field Experiments

PHOSPHORIC ACID

According to the results of field experiments, Memphis silt loam, including the white-land phase, and Huntington loam have the best natural supply of phosphoric acid. Where they have received annual applications of 200 pounds per acre of 16 per cent superphosphate over a long period, as in the experimental series where the samples were obtained, the phosphorus content of any of them would be expected to be high.

Cumberland loam ranks a little below the Memphis and the Huntington soils, but where phosphated, as it has been annually for 30 years in the experimental series from which the samples were taken, the immediate supply of available phosphoric acid is considered to be good. The annual rate of application per acre for the period 1905–1926 was 200 pounds of 16 per cent superphosphate or its equivalent. Thereafter the annual application was 150 pounds.

Of the remaining soil types, the Decatur ranks first in supply of this element but below Cumberland loam.

The Fullerton, Hartsells, Mericourt, and Montevallo soils are rated the poorest of all in phosphoric acid.

It should be noted that only unfertilized soil samples from check plots in field experiments were used for the Fullerton, Decatur, Montevallo, and Col-

bert soils. Both phosphated and unphosphated plots are represented in all the others, except soil 86, which is a sandy but highly productive alluvial soil that, so far as is known, had never received fertilizer of any kind.

POTASH

From the results of both field experiments and farmers' experience, Huntington loam and the sandy river soil, No. 86, would be expected to be, perhaps, the best supplied with potash of all the soils used. Exclusive of the white-land phase, Memphis silt loam would rank next best; the Cumberland, third; the Decatur, fourth; and the Montevallo, Colbert, Hartsells, Mericourt, and Fullerton soils and the white-land phase of Memphis silt loam in order as listed, but with little choice among the last three.

In the experimental series the usual application was 50 pounds of muriate of potash per acre annually. This was the rate of application on Cumberland loam during the period 1905–1926; thereafter, 75 pounds per acre was applied annually.

SOIL SAMPLES

All soil samples were taken in the fall of 1935. The depth of sampling was 6–8 inches, depending either on the depth of plowing or on the distance to the well-defined subsoil. Each plot was 1/40 acre, as a rule. Many plots had records of fertilizer treatments and crop yields for 25 or more years. Special care was taken to obtain representative samples. Ten subsoil samples were taken, to a uniform depth, from each plot or half plot, as in the case of both Cumberland loam and Memphis silt loam. They were well mixed, and a laboratory sample of about 3 quarts was prepared. The samples used in each method of testing were considered to be virtually identical.

General Statement of Problem

One of the important problems is to determine as far as possible the comparative merits of the methods. Unfortunately, there is no way of setting up positive standards for any soil; that is, there is no method by which the actual number of pounds per acre of immediately available phosphoric acid or potash can be determined. For this reason, no attempt was made in the soil description to give more than the general situation for each soil. Fortunately, it appears possible to reach certain conclusions based on a careful survey of all the evidence at hand, the known soil treatments, the field-crop data, and the indications as to liability to error inherent in a method.

It is, of course, important to understand that the essential requirement of either method is the getting of dependable comparative data from which practical conclusions as to fertilizer needs may be reached. Hence, the fact that the general level of the findings by one of the methods is higher than that by the other, is of minor interest.

The data calculated to pounds per acre as found by each method are given in table 1.

TABLE 1

Available plant nutrients in various soils as determined by both the Neubauer and the Fungus methods

(Data calculated to pounds per acre—2,000,000 pounds soil)

SOIL NUMBER	SOURCE OF SOIL	KIND OF SOIL	RANGE AND PLOT	PREVIOUS TREATMENT	METHOD AND FINDINGS			
					Neubauer		Fungus	
					P_2O_5	K_2O	P_2O_5	K_2O
6	W. T. Station	Memphis silt loam, white-land phase	A 1	None	42	60	44	166
7			4	PK	90	108	74	188
8			5	P	64	134	86	148
9			6	K	56	230	44	236
10			B 1	PK	64	158	52	250
11			2	P	90	194	98	216
12			3	PK	86	218	58	296
13	W. T. Station	Memphis silt loam	2 13	None	76	242	64	292
14			14	PK	122	242	104	340
15			15	P	110	194	98	296
16			18	None	78	182	64	264
17			19	PK	120	326	104	324
18			20	P	146	218	92	330
19			3 1	K	40	108	44	250
20			2	P	54	108	64	188
21			3	PK	54	218	58	194
22			10	K	66	60	64	220
23			11	P	130	96	110	172
24			12	PK	102	96	118	166
25			19	K	32	134	52	250
26			20	P	70	72	70	194
27			21	PK	62	134	80	216
28			4 21	None	54	194	98	256
29			22	PK	90	302	144	328
30			23	PK	78	242	144	308
31			24	O	40	182	80	220
32			25	O	64	302	104	292
33			26	PK	132	484	110	382
34			27	PK	112	424	132	404
82	Knoxville Station	Huntington loam	A 1	None	22	108	84	160
83			2	Manure, PK	42	158	194	210
84			3	Manure, PK	62	182	152	226
85			8	Manure	70	412	152	372
86	Knoxville Station	River soil		None	2	254	44	330
87	Knoxville Station	Cumberland loam	F 4	P	28	158	158	128
88			4L	P	46	96	118	148
89			5	PK	48	134	132	256
90			5L	PK	24	158	138	256
91			6	Manure	42	134	124	246
92			6L	Manure	42	108	138	236

TABLE 1—*Continued*

SOIL NUMBER	SOURCE OF SOIL	KIND OF SOIL	RANGE AND PLOT	PREVIOUS TREATMENT	METHOD AND FINDINGS			
					Neubauer		Fungus	
					P_2O_5	K_2O	P_2O_5	K_2O
93	Knoxville Station	Cumberland loam	7	P	46	230	132	312
94			8	PK	68	134	132	260
95			8L	PK	60	108	118	256
96			G 4	P	52	36	118	110
97			4L	P	46	108	124	128
98			5	PK	52	170	118	182
99			5L	PK	36	122	98	194
100			6	Manure, PK	52	266	104	296
101			6L	Manure, PK	28	194	118	246
102			7	P	50	218	118	274
103			8	PK	56	60	104	200
104			8L	PK	34	96	98	182
105			H 4	None	18	60	74	120
106			4L	None	26	122	74	116
107			5	PK	60	254	138	260
108			5L	PK	60	290	118	308
109			6	PK	32	194	92	288
110			6L	PK	16	206	86	270
111			7		50	376	132	336
112			8	PK	46	212	138	376
113			8L	PK	64	472	138	408
114			I 4	None	22	146	74	120
115			4L	None	18	134	64	110
116			5	PK	46	312	98	292
117			5L	PK	40	242	110	270
118			6	PK	32	254	92	274
119			6L	PK	28	206	74	256
120			7	None	20	170	98	240
121			8	PK	64	302	104	330
122			8L	PK	38	326	110	380
123			J 4	PK	32	206	124	264
124			4L	PK	38	278	158	300
125			5	PK	72	266	132	250
126			5L	PK	48	194	144	240
127			6	PK	32	254	92	292
128			6L	PK	20	134	98	256
129			7	None	44	242	98	328
130			8	K	28	194	86	288
131			8L	K	8	230	92	278
4	Jefferson Co.	Fullerton silt loam		None	34	60	52	104
143	Ed Walker		Corn	None	0	122	38	204
144	C. C. Troutman		Corn	None	0	96	30	148
145	E. G. Acuff		Corn	None	0	182	34	296
146	J. E. Wilson		Corn	None	0	122	34	200
149	James Walker		Corn	None	10	134	38	250
150	Poor Farm		Corn	None	0	72	48	128

TABLE 1—*Concluded*

SOIL NUMBER	SOURCE OF SOIL	KIND OF SOIL	RANGE AND PLOT	PREVIOUS TREATMENT	METHOD AND FINDINGS			
					Neubauer		Fungus	
					P_2O_5	K_2O	P_2O_5	K_2O
151	J. M. D. Nelson	Fullerton silt loam	Corn	None	0	108	48	188
152	J. T. Hodge		Corn	None	0	72	44	110
153	Roy French		Wheat	None	0	194	34	292
155	J. C. Wilson		Wheat	None	0	158	24	232
156	E. G. Acuff		Wheat	None	12	194	38	236
158	Ed Walker		Wheat	None	6	60	34	188
159	J. M. D. Nelson		Potato	None	8	146	64	236
160	J. C. Wilson		Potato	None	20	108	74	250
168	J. C. Wilson		Crimson clover	None	18	134	58	200
169	A. W. Kirby		Barley	None	0	122	64	182
171	Knox Co.		Rims	None	28	134	38	160
2	Jefferson Co.	Decatur silt loam			42	194	64	282
154	S. E. Ray		Wheat	None	8	146	74	240
161	H. L. Howard		Potato	None	8	108	34	200
163	Cotton Farm		Soybean	None	18	254	64	328
165	Gentry		Flax	None	26	72	86	140
166	Gentry		Flax	None	16	60	98	166
1	Cumberland Co.	Hartsells fine sandy loam		None	32	158	34	264
132	Jas. Smith		A 1 4	PK	8	24	44	166
133			A 2 4	PK	8	72	34	194
134			A 3 4	PK	2	96	64	204
135			A 4 4	O	4	146	24	260
136			A 5 4	PK	16	84	86	194
137			A 3 5	P	10	84	74	148
138			A 4 5	O	10	146	44	240
139			A 5 5	P	26	158	110	220
140				None	0	170	80	324
141				None	0	194	34	300
142	Homestead			None	10	170	24	260
65	Mericourt Station	Mericourt silt loam	3 9S	PK	36	170	118	304
66			3 20S	P	16	146	98	172
67			0 9	O	0	314	48	328
68			3 9N	PK	34	182	86	270
69			3 20N	P	16	96	70	198
70			0 8	P	10	122	58	348
3	Jefferson Co.	Montevallo silt loam		None	40	374	58	428
148	F. N. Hamilton		Corn	None	2	182	34	236
162	Cotton Farm		Soybean	None	16	158	44	250
167	D. H. Tunnell		Corn	None	0	108	74	98
172	Montvale		Wheat		16	48	58	120
5	Russell Ford	Colbert silt loam		None	24	72	74	120
147	J. D. Shipe		Corn	None	0	108	38	216
157	J. D. Shipe		Wheat	None	6	36	30	98

Discussion of Data

Comparative adaptability of the Neubauer and fungus methods to different soil types

Phosphoric acid

The data of table 1 show conclusively that both the Neubauer and the Cunninghamella methods make positive distinctions between phosphated and unphosphated plots in an experimental series, as well as between certain of the soil types with regard to the supply of available phosphoric acid. It is noticeable that for the river soil and for 8 of the soil types, beginning with Huntington loam and ending with Colbert silt loam, the results were on a consistently higher level by the Cunninghamella method than by the Neubauer method. On the other hand, for Memphis silt loam and its white-land phase, involving a total of 29 soil samples, the data from the Cunninghamella method were at nearly the same level as those from the Neubauer method. This inconsistency is so outstanding as to require consideration, for it is evident that one or the other of the methods must be at fault. Field experiments, carried out for 26 years on these soils, showed the soils to be exceptionally well supplied with phosphoric acid. The Cunninghamella method, therefore, though showing differences due to soil treatment, gives results on decidedly too low a level for Memphis silt loam.

Although Memphis silt loam affords an outstanding example of disagreement, as far as the comparative placement of soil types is concerned, further consideration of the data raises a similar question with regard to other soils. Cumberland loam, for example, is a fertile soil, producing much larger crops than do most types and appreciably less responsive to phosphate treatment. This rating is indicated clearly by the Cunninghamella method. On the other hand, the results by the Neubauer method are decidedly too low.

In the sandy river soil, No. 86, a very low content of P_2O_5, as found by both methods, is probably correct, but the practical interpretation of the result would have to be made on an entirely different basis from that adapted to an upland soil; the river soil was not found responsive to P_2O_5, probably on account of the favorable permeability conditions. The conclusion is therefore reached that different soil types may require different standards of interpretation by either method.

Attention is directed to another matter, that is, the frequency with which the Neubauer method gives a zero content of phosphoric acid for soils low in this element. These soils are indicated as very deficient, it is true, but they always contain a positive supply of available phosphoric acid, most of them having produced, without phosphate, approximately 25 bushels of corn per acre the year the soil samples were taken. The matter of zero results raises the question of liability to error, which may account for some rather wide discrepancies between results obtained by the two methods for individual soil samples.

Potash

The potash data by the two methods appear, in a general way, to be more consistent, so far as all soil types are concerned, than the data for phosphoric acid; that is, there is no pronounced change in the level for any particular soil type. The effects of fertilizer applications are, in general, plainly indicated by each method, but the individual disagreements are even more numerous than in the case of P_2O_5.

TABLE 2

Tentative standards for comparison of data obtained by the Neubauer and Fungus methods*

(In pounds per acre)

	VERY LOW	LOW	MEDIUM	HIGH	VERY HIGH
Neubauer method:					
P_2O_5	1–20	21–40	41–60	61–80	>80
K_2O	1–100	101–150	151–200	201–250	>250
Fungus methods:					
P_2O_5	1–50	51–90	91–130	131–170	>170
K_2O	1–150	151–220	221–290	291–360	>360

* The general import of the terms used is as follows:

P_2O_5:

Very low, extremely deficient in P_2O_5.

Low, deficient in P_2O_5 for all crops. Use of phosphate an essential to profitable farming.

Medium, response to P_2O_5 moderate to none. No special need for P_2O_5 under good livestock system of farming. Cotton, tobacco, and truck crops usually show response.

High, no immediate response to P_2O_5 by any crop.

Very high, will stand more than a year's cropping without response to P_2O_5.

K_2O:

Very low, nearly all crops benefited, except possibly corn and oats, both of which would likely respond to K_2O after removal of a succession of hay crops such as lespedeza.

Low, hay, truck crops, tobacco, and cotton respond markedly to applications of K_2O. Not usually needed by corn and oats.

Medium, K_2O not required in livestock farming under good methods. Under many conditions, moderate applications of K_2O are profitable for truck crops and tobacco. Little response by general farm crops.

High, no immediate response to K_2O by any crop.

Very high, will stand more than a year's crop removal without response to potash.

STANDARDS OF INTERPRETATION

In the pursuit of the present study it appeared desirable to set up standards for the comparative study of the data. These standards may not be those finally adopted for the purpose of making practical recommendations for Tennessee soils, but they are considered to be approximately in accord with the results of the field experiments. Standards for the Neubauer method were delimited in groups somewhat arbitrarily, but with regard to the field data. Standards were then developed for the Fungus methods with a view to making

the two sets comparable, if possible. To accomplish this result, dependence was placed only on cut-and-dry procedure. The standards, as obtained in this way, are shown in table 2.

TABLE 3

Group placements of available P_2O_5 for each of 10 soils as indicated by both the Neubauer and the Cunninghamella methods

GROUP	MEMPHIS SILT LOAM		WHITE-LAND PHASE MEMPHIS SILT LOAM		HUNTINGTON LOAM		CUMBERLAND LOAM		FULLERTON SILT LOAM		DECATUR SILT LOAM		HARTSELLS FINE SANDY LOAM		MERICOURT SILT LOAM		MONTEVALLO SILT LOAM		COLBERT SILT LOAM	
	N.*	C.†	N.	C.	N.	C.	N.	C.	N.	C.	N.	C.	N.	C.	N.	C.	N.	C.	N.	C.
Very low...	0	1	0	2			6	0	16	13	4	1	10	7	4	1	4	2	2	2
Low.....	3	9	0	4	1	1	16	7	2	5	1	5	2	4	2	3	1	3	1	1
Medium....	3	9	2	1	1	0	19	25	0	0	1	0	0	1	0	2	0	0	0	0
High.....	7	3	2	0	2	2	4	13	0	0	0	0	0	0	0	0	0	0	0	0
Very high..	9	0	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total number samples.....	22	22	7	7	4	4	45	45	18	18	6	6	12	12	6	6	5	5	3	3

* N. = Neubauer.

† C. = Cunninghamella.

TABLE 4

Group placements of available K_2O for each of 10 soils as indicated by both the Neubauer and the Aspergillus niger *methods*

GROUP	MEMPHIS SILT LOAM		WHITE-LAND PHASE MEMPHIS SILT LOAM		HUNTINGTON LOAM		CUMBERLAND LOAM		FULLERTON SILT LOAM		DECATUR SILT LOAM		HARTSELLS FINE SANDY LOAM		MERICOURT SILT FOAM		MONTEVALLO SILT LOAM		COLBERT SILT LOAM	
	N.*	A.N.†	N.	A.N.	N.	A.N.	N.	A.N.	N.	A.N.	N.	A.N.	N.	A.N.	N.	A.N.	N.	A.N.	N.	A.N.
Very low...	4	0	1	1	1	0	5	8	5	4	2	1	6	1	1	0	1	2	2	2
Low.....	4	8	2	3	1	2	11	4	9	7	2	2	1	5	2	2	1	0	1	1
Medium....	4	4	2	2	1	1	8	21	4	5	1	2	5	4	2	1	2	2	0	0
High.....	5	8	2	1	2	1	9	8	0	2	1	1	0	2	0	3	0	0	0	0
Very high..	5	2	0	0	0	1	12	4	0	0	0	0	0	0	1	0	1	1	0	0
Total number samples.....	22	22	7	7	5	5	45	45	18	18	6	6	12	12	6	6	5	5	3	3

* N. = Neubauer.

† A.N. = *Aspergillus niger.*

COMPARATIVE SOIL RATINGS ON THE BASIS OF GROUP STANDARDS

By the aid of the standards, comparison of the data by the two methods is simplified, as illustrated in tables 3 and 4. These tables emphasize the general conclusions previously reached, both as to the marked similarity of the place-

ments obtained by both methods for the majority of the soils and as to the dissimilar placements in respect to P_2O_5 for both Memphis silt loam and Cumberland loam, the Neubauer method giving high, but apparently proper, indications for the former soil type but decidedly too low indications for the latter soil type. It is important to consider that the data for each type of soil in both tables are general in nature, and that little light is thrown, therefore, on the numerous individual inconsistencies noticeable in table 1, a subject which will now be discussed.

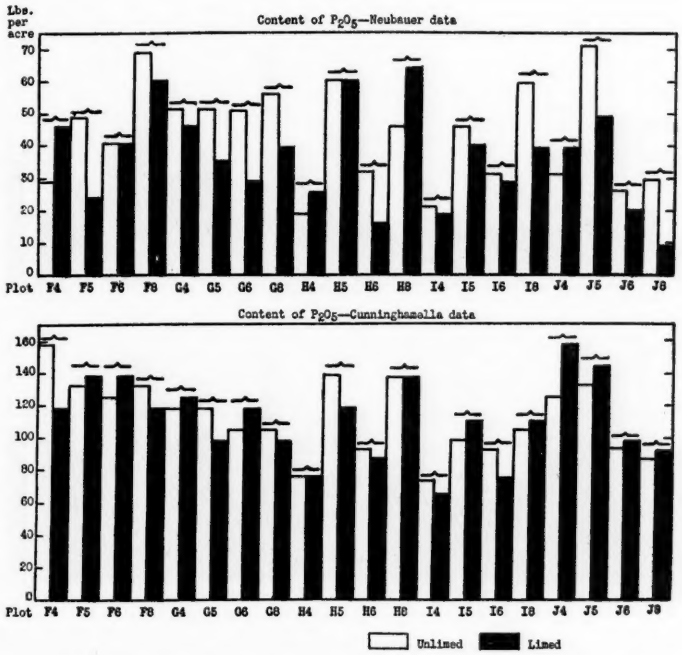

FIG. 1. P_2O_5 CONTENT OF LIMED AND UNLIMED PLOT SECTIONS OF CUMBERLAND LOAM AT THE KNOXVILLE STATION, AS DETERMINED BY THE NEUBAUER AND THE CUNNINGHAMELLA METHODS

INHERENT SOURCE OF ERROR

Every analytical method carries certain inherent error; that is, no method is absolutely accurate. Obviously, methods as different as those under consideration might differ in the extent or seriousness of this error. Figures 1 and 2 and table 5 were prepared in order to throw light on this subject. The basic data are found in the Cumberland loam group of table 1, which includes all the plots having limed and unlimed sections. Fortunately, for the present purpose, the sections of any one plot may be considered as duplicates, to the extent that they would be expected to be closely alike in their contents of

P_2O_5 and K_2O. Applications of 1 ton of burnt lime per acre were made twice in the 30-year period, the first time in 1905, and the second in 1917. The effects of liming on crop yield have been noticeable even in recent years, as shown in table 6, which gives the annual crop production and the percentage variation from the plot average between the limed and the unlimed sections.

In order to present the analytical findings on a comparable basis for the Neubauer and the Fungus methods, the percentage difference between the data for the limed and unlimed section of each plot is given in table 5, the

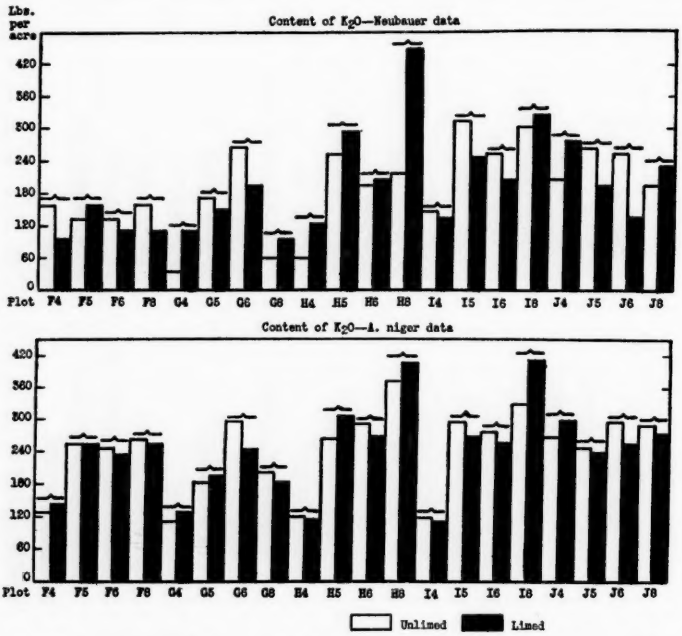

FIG. 2. K_2O CONTENT OF LIMED AND UNLIMED PLOT SECTIONS OF CUMBERLAND LOAM AT THE KNOXVILLE STATION, AS DETERMINED BY THE NEUBAUER AND THE ASPERGILLUS NIGER METHODS

basis of calculation being the average number of pounds of P_2O_5 or of K_2O for the two sections of a plot. The maximum difference for P_2O_5 was 111 per cent by the Neubauer method, as compared with 29 per cent by the Cunninghamella method; and 9 plots differed by 40 or more per cent by the former method, whereas only 3 plots differed by more than 20 per cent by the latter method. Similarly, the maximum difference for potash was 100 per cent by the Neubauer method, as compared with only 19 per cent by the *A. niger* method. The average differences for P_2O_5 and K_2O by the Neubauer method

were 37 and 34 per cent, respectively, against only 11 and 9 per cent by the Fungus methods. There must, of course, be some actual soil differences, but these would be the same for each method. How much of the difference can be attributed to the soil is not known, but it can be reasonably assumed to be, on the average, less than 11 per cent for P_2O_5 and less than 9 per cent for potash, which represent the additive effects of both the soil difference and the

TABLE 5

Variation in P_2O_5 and K_2O content between unlimed and limed plot sections—Cumberland loam at the Knoxville Station

PLOT	NEUBAUER METHOD		FUNGUS METHODS	
	P_2O_5	K_2O	P_2O_5	K_2O
	per cent	*per cent*	*per cent*	*per cent*
F-4	49	49	29	15
F-5	67	16	4	0
F-6	0	21	11	4
F-8	13	21	11	2
G-4	12	100	5	15
G-5	36	34	19	6
G-6	60	31	13	19
G-8	49	46	6	9
H-4	36	68	0	3
H-5	0	13	16	17
H-6	66	6	7	6
H-8	33	73	0	8
I-4	20	9	15	9
I-5	14	25	12	8
I-6	13	21	22	7
I-8	51	8	6	15
J-4	17	31	24	13
J-5	40	31	9	4
J-6	46	62	6	13
J-8	111	17	7	4
Average variation.	37	34	11	9

inherent error in the Fungus methods. This estimate is corroborated by the crop data of table 6. Undoubtedly the differences in crop yields between the limed and the unlimed halves of the plots must be attributed chiefly to the effects of the liming. Even so, the total difference amounts to only 11.32 per cent, on the average, when calculated in a manner similar to that by which the percentages were obtained for the soil analytical data given in table 5. The conclusion is reached, therefore, that the Fungus methods far surpass the Nebauer method, insofar as inherent liability to error is concerned. In fact, this liability to error appeared to be a serious handicap to the Neubauer method.

COMPARATIVE AVAILABILITY OF DIFFERENT PHOSPHATES

Short methods are sometimes recommended as a means of obtaining an index of the availability of different phosphates when applied to the soil. Table 7 gives the comparative rating in availability of eight different phosphates for each of five soils known to be deficient in phosphoric acid, mono-

TABLE 6

Relative productivity of Cumberland loam plots, as indicated by crop production for 5 years, 1931–1935. Total average annual yields of cowpeas and wheat, both straw and grain included

(Both cowpeas and wheat grown annually on all plots except on H-5, where only wheat was grown, and on H-8, where only cowpeas were grown)

PLOT	FERTILIZER	DISPOSITION OF COWPEA CROPS	UNLIMED	LIMED	AVERAGE	PERCENTAGE DIFFERENCES IN PRODUCTION BETWEEN UNLIMED AND LIMED HALVES, ON BASIS OF PLOT AVERAGE
			cwt.	*cwt.*	*cwt.*	
F-4	P	Turned under	30.9	32.7	32.7	5.50
5	PK	Turned under	51.3	50.8	51.1	0.98
6	Manure	Removed	64.5	65.7	65.1	1.84
8	PK	Turned under	68.1	69.7	68.9	2.32
G-4	P	Removed	23.8	20.2	22.0	16.36
5	PK	Removed	32.9	39.5	36.2	18.23
6	Manure and PK	Removed	58.5	62.4	60.5	6.45
8	PK	Removed	35.8	45.8	40.8	24.51
H-4	None	Turned under	35.2	40.9	38.1	14.96
5	PK	None grown	20.0	22.7	21.4	13.09
6	PK	Turned under	49.7	60.3	55.0	19.27
8	PK	Turned under	30.6	36.2	33.4	16.73
I-4	None	Removed	20.0	24.2	22.2	18.47
5	PK	Turned under	53.5	59.7	56.6	7.42
6	PK	Turned under	51.9	62.0	57.0	17.72
8	PK	Turned under	59.5	66.1	61.8	10.68
J-4	PK	Turned under	54.2	57.1	55.7	5.21
5	PK	Turned under	56.5	62.0	59.3	9.27
6	PK	Turned under	47.7	55.6	51.7	15.28
8	K	Turned under	48.1	59.1	48.6	2.06
Average			44.5	49.1	46.9	11.32

calcium phosphate being taken as the standard of comparison, or 100 per cent. Meta-A was much more readily water soluble than was Meta-B. As determined by the Neubauer method, the average standing of the phosphates was monocalcium, first, 100 per cent; fused, second, 97 per cent; dicalcium, third, 92 per cent; triple super, fourth, 74 per cent; meta-A, fifth, 64 per cent;

tricalcium, sixth, 60 per cent; meta-B, seventh, 18 per cent; and rock phosphate, eighth, 13 per cent. As determined by the Cunninghamella method, the order was monocalcium, first, 100 per cent; triple super, second, 96 per cent; dicalcium, third, 87 per cent; fused, fourth, 81 per cent; meta-A, fifth, 70 per cent; tricalcium, sixth, 52 per cent; meta-B, seventh, 43 per cent; and rock phosphate, eighth, 6 per cent.

Comparative field trials with various phosphates were made on all the soils except the Decatur. Corn, wheat, millet, cowpeas, soybeans, and potatoes were the crops used. The trials were not sufficient to establish differences, if any, in the availability of the phosphates as affected by type of soil. No positive difference appeared in effects on crop yield between monocalcium,

TABLE 7

Comparative availability of different phosphates as determined by the Neubauer and Cunninghamella methods—monocalcium phosphate taken as the standard, or 100 per cent

PHOSPHATE	COLBERT		DECATUR		FULLERTON		HARTSELLS		MONTEVALLO	
	N.*	C.†	N.	C.	N.	C.	N.	C.	N.	C.
Monocalcium	100	100	100	100	100	100	100	100	100	100
Dicalcium	97	74	75	106	102	81	82	91	104	84
Fused	...	...	85	83	...	...	110	84	97	80
Meta-A	41	81	70	100	72	66	68	47	69	54
Meta-B	39	54	5	69	9	41	3	25	32	27
Rock phosphate	...	...	0	9	...	...	0	7	38	3
Tricalcium	80	56	28	51	76	43	34	77	84	35
Triple super	66	92	68	106	102	87	54	94	81	100

* N. = Neubauer.

† C. = Cunninghamella.

triple super, dicalcium, and calcium metaphosphate, pound for pound of total P_2O_5 applied; on the other hand, fused and tricalcium phosphate almost always took an appreciably lower ranking, which was not unexpected, in view of the fact that probably not over three fourths of the original fluorine content of the rock had been displaced in the process of manufacture.

As to the results by the methods under comparison, not only is there an evident lack of harmony, but neither method indicated the proper standing of metaphosphate, which was rated much too low. Otherwise, the Cunninghamella results are closely in harmony with the field data. On the other hand, the results by the Neubauer method are decidedly at variance with the field data and with expectations based on composition of the materials. The phosphoric acid in triple superphosphate, for example, is virtually all in the monocalcium form, but by the Neubauer method its rating was only 74 per cent. Another example is the high rating of 97 per cent for fused phosphate, which, as previously stated, was almost always appreciably excelled by the four leading phosphates.

RAPID CHEMICAL TEST METHOD

A rapid chemical test method, as used at the Indiana Station, was tried in comparison with the Neubauer and the Fungus methods. In round numbers, the rapid method was in agreement with the Neubauer, on the basis of a simplified or 3-group standard, for P_2O_5 in 60 per cent of the soil samples, and for K_2O in 67 per cent. In comparison with the Fungus tests, the rapid test gave a 60 per cent agreement for P_2O_5 and a 75 per cent agreement for K_2O. The P_2O_5 test by the rapid method was especially out of harmony with the others in the case of soils with medium or high content. On the other hand, the standing of the K_2O test by the rapid method was good at all levels.

SOURCES OF ERROR IN THE NEUBAUER METHOD

No special study was made to account for the evident large error to which the Neubauer method is liable. Two sources are recognized. One is the large amount of P_2O_5 and K_2O in the hundred seeds of rye sown in each trial. The P_2O_5 content of the seed used was approximately 24 mg., equivalent to 480 pounds of P_2O_5 per acre, or nearly 10 times the amount contained in an average soil; and the content of K_2O was approximately 16 mg. Variations in the individual lots of seed are common, however, and, for P_2O_5, may amount to 2 mg., or 40 pounds per acre. It is unfortunate that the exact allowances for the seed used cannot be known. The other source of error lies in the analytical process, and though this error may be small, it is a factor to be considered.

COMPARATIVE ECONOMY OF THE NEUBAUER AND THE FUNGUS METHODS

With the Neubauer method, two men complete 48 soil samples a week. Ten times this number can be handled by the same force, using the Fungus methods. Also, the equipment for the Fungus methods is comparatively simple, whereas a fairly complete chemical laboratory is required for the Neubauer method. The time required for completion of a soil analysis is an item of importance; from the receipt of the soil sample to the rendering of a report, nearly 20 days would be needed for the Neubauer method as compared with only 3 or 4 days for the Fungus methods.

SUMMARY

In a comparison of the Neubauer and the Fungus methods for the determination of the fertilizer needs of a soil, 129 samples of soil, representing 9 different soil types, 1 soil type phase, and 1 land type, were used.

The majority of the soil samples were obtained from experimental plots for many of which records of crop yields and fertilizer treatments were available for 25 or more years.

The Neubauer and the Fungus methods made positive distinctions between fertilized and unfertilized plots on the same kind of soil.

The comparative rating of various soil types by the Neubauer and the Fungus methods was, in the majority of cases, in general harmony with the

known condition of the soils. A marked exception was the low rating of Memphis silt loam by the Cunninghamella method as compared with the apparently proper rating by the Neubauer method. On the other hand the rating of a fertile Cumberland loam was appreciably more in harmony with crop production by the Cunninghamella method than by the Neubauer method.

The evidence was considered conclusive that different soils might require materially different standards of interpretation, and specific instances were pointed out.

Although there was a general agreement in the data obtained by the Neubauer and the Fungus methods when a number of samples could be averaged, there was frequent and wide disagreement in individual samples.

Standards of interpretation were set up for the purpose of a more specific comparison of the results obtained by the methods.

Cumberland loam samples from a long-continued series of fertilizer experiments furnished evidence as to the comparative liability to error of the methods, and the conclusion was reached that the Neubauer method for both P_2O_5 and K_2O was liable to serious error in individual samples and that the Fungus methods were far superior in this respect because of their low inherent source of error.

The Neubauer and the Cunninghamella methods as means of obtaining an index of the availability of different phosphates for each of five types of soil were compared. For calcium metaphosphates, neither method gave results in harmony with the data from field experiments. The ranking of the other phosphates by the two methods was in wide disagreement, but that by the Cunninghamella method was in close harmony with the field results.

Trial was made of a rapid chemical test method as used at the Indiana Station. Results by the rapid method were in reasonable agreement with the Neubauer data for P_2O_5 in 60 per cent of the soil samples, and for K_2O in 67 per cent. The agreement between the rapid test method and the Fungus methods was 60 per cent for P_2O_5 and 75 per cent for K_2O. The rapid method for P_2O_5 gave results especially out of harmony with the others in the case of soils of medium or high content. On the other hand, it gave good results for K_2O at all levels.

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BEHAVIOR OF CALCIUM, MAGNESIUM, AND POTASSIUM SULFATES, AS INFLUENCED BY LIMESTONE AND BY DOLOMITE—A LYSIMETER STUDY

W. H. MacINTIRE, W. M. SHAW, J. B. YOUNG, AND BROOKS ROBINSON

The University of Tennessee Agricultural Experiment Station

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In unfertilized soils, the plant is primarily dependent upon two sources of sulfates, those engendered within the soil, and those brought by rain waters (17, 20). It has been shown that rain waters bring sulfates of calcium, magnesium, and potassium to the soil, and that location, season, and proximity to coal-burning operations materially influence the amounts of these increments (6, 7, 14, 15, 17). Recently, however, Alway, Marsh, and Methley (1) demonstrate the infusion of atmospheric SO_2 into the soil and cited four contributions relative to the inhalation of atmospheric sulfur dioxide by plants.

Since heavy fertilization has been common in those regions where several crops per annum are harvested, the amounts of sulfates supplied by superphosphate and by the potassium, magnesium, and ammonium sulfates of mixed fertilizers have probably provided ample quantities of nutrient sulfur. The increasing usage of phosphatic concentrates, however, has resulted in revived discussions and claims as to the adequacy of the sulfates supplied to crops by natural agencies.

RELATED FINDINGS

Some of the residual effects of ammonium sulfate and calcium sulfate in the soil of the Jordan Fertility Plats have been determined (3, 4, 24). Little is known, however, as to any differential effect that variation in cation combination of the SO_4 of sulfate additions may exert upon (a) conservation of sulfates in the soil, and (b) extent of interchange reactions, as registered by altered outgo of bases.

Previous lysimeter studies have indicated that a near-balance exists between the amounts of sulfates brought to unlimed fallow soils and those leached from such soils (2, 6, 7, 14, 15, 17), that the intensity of the initial accelerative effect of economic liming treatments upon sulfate outgo is not sustained (2, 6, 7, 17), and that clay subsoils have a retentive capacity for the sulfates that leach from overlying soils (2, 14, 19).

Although magnesium sulfate is much more soluble than calcium sulfate, the behavior of additions of the more soluble sulfate to soils of the humid region is influenced by the content of exchangeable calcium, which usually exceeds

the content of exchangeable magnesium. Hence, when one of these two sulfates is added to the soil, the proportion that leaches in the form applied and the proportion that enters into the soil system through exchange reactions, are governed by those variables. The differential effects of lime and magnesia upon sulfate generation and outgo are known (8, 14, 15, 17, 19). Although soil-engendered sulfates may exert little effect on potassium outgo (13, 15, 17), a portion of the potassium added as sulfate may be fixed in an exchangeable form, whereas another portion may be so tenaciously held as to resist rigorous chemical extractions (22).

OBJECTIVES

The present lysimeter experiment was initiated to study the fate of annual equivalent incorporations of calcium, magnesium, and potassium sulfates. The three principle objectives were to determine (a) whether the cation combination influences the conservation of added SO_4, (b) the nature and extent of interchange reactions induced by each of the three sulfates, and (c) any divergent influence that single economic incorporations of limestone and of dolomite exert on (a) and (b).

TABLE 1

Analyses of the brown clay loam used in the study of the history of annual equivalent additions of sulfates of calcium, magnesium, and potassium

SULFUR AS $CASO_4$ ⇨		REPLACEABLE BASES†			NITROGEN
Total*	Water-soluble	CaO	MgO	K_2O	
per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
0.212	0.019	0.192	0.036	0.081	0.204

* Na_2CO_3—Na_2O_2 fusion (10).

† By boiling 0.1 *N* NH_4Cl (12).

EXPERIMENTAL

The soil used was a brown silty clay loam that had been in sod for many years and was unusually rich in exchangeable bases and organic matter (table 1). The sod was skimmed off and discarded. The soil had an initial pH of 6.77, which rose to 6.89 after aqueous leaching. Seven annual full-depth incorporations of each of the three sulfates were made, at the equivalent-rate of 400 pounds of calcium sulfate per 2,000,000 pounds of surface soil, in asphaltum-coated outdoor lysimeters having an area of 1/20,000 acre. The metal surface of the leachate receptacles were likewise protected by an asphaltum coating. Annual incorporations of potassium sulfate were also made at the $CaSO_4$-equivalent rate of 800 pounds. The untreated control soils were also worked when the annual incorporations of sulfates were made. Single full-depth incorporations of limestone and of dolomite, both of 100 mesh, were also included as initial supplements to the several sulfates, both supplements being at the equivalent-rate of 2 tons of $CaCO_3$ per 2,000,000 pounds of soil. The total sulfur content of the limestone supplement was equivalent to only 1.7 pounds

of $CaSO_4$; but, because of its content of zinc sulfide as sphalerite, the supplement of dolomite introduced the equivalence of 55 pounds of $CaSO_4$. The rain waters were collected at each end of the lysimeter installation. The collections of the rain waters and leachates of each annual period were brought to composite acidic solutions in glass containers, and the SO_4, calcium, magnesium, and potassium contents of each annual composite were determined.

Sulfate conservation

Expressed as $CaSO_4$, the sulfate contents of the rain waters and of the leachates from each soil treatment are given, in table 2, for the seven annual periods. The increments of sulfates brought to the soil by rain waters show the usual variation ascribed to extent and proximity of coal consumption and also to location of receptacles. Any variations in sulfate increment are obliterated, however, during the passage of the rain waters through the untreated soil. Since the rain waters were caught in receptacles and collected in containers that were asphaltum-coated, the point raised by Alway, Marsh, and Methley (1) as to the action of atmospheric SO_2 upon the surface of galvanized iron does not apply to the rain waters and leachates of the present experiment.

To determine the respective recoveries from the three added sulfates, the mean outgo from the untreated units was deducted from each 7-year outgo from the 2,800-pound and 5,600-pound sulfate treatments.

Complete SO_4 recoveries were obtained only from the 2,800-pound-rate additions of magnesium and potassium sulfates, incorporated with the dolomitic supplement. If the 55-pound sulfate-equivalent of the sphalerite content of the dolomite were counted as a potential sulfate addition, however, these two complete recoveries would be reduced to recoveries of 98 per cent. The mean conservation of 4.3 per cent found for the other seven sulfate treatments of 400 pounds each per annum was, however, equivalent to 120 pounds of calcium sulfate.

No repressive effect upon the outgo of sulfates from the calcium sulfate addition was induced by the 2-ton supplement of either limestone or dolomite. The two types of limestone likewise failed to repress outgo of sulfates from the additions of magnesium sulfate. The difference in solubilities of the two sulfates is minimized in the rainwater leachings, the mean recoveries of SO_4 from the calcium sulfate and magnesium sulfate additions being 95.4 per cent and 97.1 per cent, respectively. In previous studies where no sulfates were added, additions of magnesic materials caused a greater outgo of sulfates. This was attributed to a larger supply of sulfates resultant from the greater accelerative effect of magnesia upon sulfofication (6, 14, 15, 19).

The sulfate outgo from the unsupplemented potassium sulfate additions at the 400-pound rate was substantially the same as the sulfate outgo from the unsupplemented additions of calcium and magnesium sulfates. Both limestone and dolomite induced increases in sulfate outgo from the potassium sulfate additions at the 400-pound rate, and respective recoveries of 99 and

TABLE 2

Outgo of sulfates from seven annual equivalent additions of calcium, magnesium, and potassium sulfates, with and without limestone and dolomite

TANK NUMBER	TREATMENT		SULFATE OUTGO, IN TERMS OF POUNDS OF $CaSO_4$ PER 2,000,000 POUNDS OF SOIL									
	Annual sulfate additions, in terms of 400 pounds $CaSO_4$ =	Single initial addition = 2 tons of $CaCO_3$	1930–31	1931–32	1932–33	1933–34	1934–35	1935–36	1936–37	1930–1937		
										Total	Derived from addition*	
											Pounds	Per cent
617	Rainwater	None	124	102	90	71	90	110	106	693	.....	....
618	None	None	312	341	218	160	230	224	161	1,646	.....	....
619	$CaSO_4$	None	642	694	599	514	672	640	506	4,267	2,624	93.7
20	$CaSO_4$	Limestone	739	690	596	582	621	625	531	4,384	2,741	97.9
21	$CaSO_4$	Dolomite	749	690†	566	594	551	620	518	4,288	2,645	94.5
622	$MgSO_4$	None	671	750	571	489	665	631	536	4,313	2,670	95.4
23	$MgSO_4$	Limestone	757	649	570	545	641	620	547	4,329	2,686	95.9
24	$MgSO_4$	Dolomite	774	742	591	536	635	600	564	4,442	2,799	100.0
625	K_2SO_4	None	670	747	582	466	666	609	517	4,257	2,614	93.4
26	K_2SO_4	Limestone	763	712	634	540	649	582	534	4,414	2,771	99.0
27	K_2SO_4	Dolomite	760	773	608	534	642	611	517	4,445	2,802	100.1
28	$2 \times K_2SO_4$	None	1,036	1,059	978	831	1,071	983	910	6,868	5,225	93.3
29	$2 \times K_2SO_4$	Limestone	1,173	1,054	978	914	1,015	1,001	869	7,004	5,361	95.7
30	$2 \times K_2SO_4$	Dolomite	1,168	1,049	1,013	761	1,037	982	880	6,890	5,247	93.7
631	None	None	307	347	220	154	231	211	170	1,640	.....	....
632	Rainwater	None	81	88	76	58	80	96	105	584	.....	....
Inches of rainfall			38.83	55.33	55.95	38.45‡	61.77	47.23§	52.05	349.6	.....	....

* Total additions of 2,800 pounds and 5,600 pounds $CaSO_4$ or equivalent.

† Computed.

‡ An additional collection of 12.16 inches was made in rain gauges during a period when the tanks were covered.

§ An additional collection of 2.35 inches was made in rain gauges during a period when the tanks were covered.

100 per cent. As noted, however, the latter value would be reduced to 98.1 per cent, were the sulfate-equivalent of the sphalerite content of the dolomite computed as an additive treatment. The recovery of SO_4 from the unsupplemented additions of K_2SO_4 at the double rate of 800 pounds was almost identically proportionate to the recovery of SO_4 from the 400-pound additions. Neither limestone nor dolomite showed any material influence upon the conservation of sulfates from the double, or 800-pound, annual addition of K_2SO_4.

Outgo of calcium

The amounts of calcium, in terms of $CaCO_3$, that passed from the controls and from different treatments during the 7 year period are shown in table 3.

The outgo of calcium from the unsupplemented calcium sulfate addition was virtually identical with that found for the same addition with its dolomitic supplement. This is in accord with previous findings to the effect that the outgo of calcium from clay loam soils may not be enhanced by economic additions of dolomite (16), at least for several years, a result that is reflected in the composition of plant growth. The mean of increases in calcium outgo from the calcium sulfate additions, alone and also with dolomite, represents only 68 per cent of the amounts of calcium supplied by the added calcium sulfate.

Each year, and especially during the first two years, the maximal outgo of calcium from the calcium sulfate series was induced by the limestone supplement. If the entire amount of calcium added as sulfate was removed by leaching, as was indicated by the 98 per cent recovery of SO_4, the increase in the mean annual $CaCO_3$-equivalent outgo of calcium derived from the 2-ton limestone supplement was only 167 pounds. The increase in calcium outgo induced by the limestone supplement was somewhat greater in its association with the sulfate of calcium than with the other two sulfates.

The additions of magnesium sulfate induced exchange reactions that caused a substantial increase in the outgo of calcium from the unlimed soil. Magnitude of increases in calcium outgo from this series was in the ascendant order, sulfate alone, sulfate + dolomite, and sulfate + limestone. The increased outgo of calcium induced by the limestone supplement, in its association with the seven annual additions of magnesium sulfate, was approximately 1,000 pounds less than the outgo of calcium induced by the limestone in its association with calcium sulfate. The increase in calcium outgo attributable to the dolomite supplement was only 146 pounds for the 7-year period. It is evident that the additions of magnesium sulfate replaced a considerable quantity of the native calcium and also effected some exchange for the supplies of sorbed calcium, unless the magnesium sulfate additions caused more of the calcium content of the rainwaters to pass through the soil. If the 78-pound per annum increase in calcium outgo from the seven unsupplemented annual incorporations of magnesium sulfate is attributed solely to exchange reactions, then the extent of such reactions was only one fourth of the potential exchange capacity of the added magnesium sulfate.

TABLE 3

*Outgo of calcium as influenced by seven annual equivalent incorporations of sulfates of calcium, magnesium, and potassium**

TANK NUMBER	TREATMENT		CALCIUM LEACHED, IN TERMS OF POUNDS $CaCO_3$ PER 2,000,000 POUNDS OF SOIL									
	Annual sulfate additions, in terms of 400 pounds $CaSO_4$ ⇔	Single initial addition ⇔ 2 tons of $CaCO_3$	1930–31	1931–32	1932–33	1933–34	1934–35	1935–36	1936–37	1930–1937 Total	1930–1937 Increase Total	1930–1937 Increase Annual
617	Rainwater	None	264	209	172	153	149	138	183	1,268	.....	...
618	None	None	495	609	446	463	386	456	292	3,147	.....	...
619	$CaSO_4$	None	650	700	582	632	649	674	461	4,348	1,314	188
20	$CaSO_4$	Limestone	945	936	774	723	734	806	604	5,522	2,488	355 [167]†
21	$CaSO_4$	Dolomite	717	748	599	600	546	635	505	4,350	1,316	188 [0]
622	$MgSO_4$	None	603	660	473	454	476	549	366	3,581	547	78
23	$MgSO_4$	Limestone	921	656	686	608	582	602	472	4,527	1,493	213 [135]
24	$MgSO_4$	Dolomite	727	693	575	409	476	461	386	3,727	693	99 [21]
625	K_2SO_4	None	589	658	501	447	403	434	332	3,364	330	47
26	K_2SO_4	Limestone	927	796	682	561	553	529	413	4,461	1,427	204 [157]
27	K_2SO_4	Dolomite	653	690	497	438	453	456	336	3,523	489	70 [23]
628	$2 \times K_2SO_4$	None	645	669	603	495	475	441	376	3,704	670	96
29	$2 \times K_2SO_4$	Limestone	1,110	902	712	630	522	539	392	4,807	1,773	253 [157]
30	$2 \times K_2SO_4$	Dolomite	799	692	616	346	450	451	338	3,692	658	94 [−2]
631	None	None	449	549	438	404	371	446	263	2,920	.....	...
632	Rainwater	None	138	126	140	104	112	121	140	881	.....	...
Inches of rainfall.....			38.83	55.33	55.95	38.45‡	61.77	47.23§	52.05	349.6	.....	...

* Total additions of 2,800 pounds and 5,600 pounds $CaSO_4$ or equivalent.

† Bracketed figures show the increases attributable to either limestone or dolomite.

‡ An additional collection of 12.16 inches was made in rain gauges during a period when the tanks were covered.

§ An additional collection of 2.35 inches was made in rain gauges during a period when the tanks were covered.

If the enhancement in calcium outgo induced by the seven unsupplemented annual additions of potassium sulfate at the 400-pound rate is a true index of the replacement of Ca by K, the sulfate functioned to only 32 per cent of its potential exchange capacity. The corresponding enhancement in calcium outgo induced by the unsupplemented 5,600-pound total of added K_2SO_4 was practically double the enhancement in calcium outgo from the 2,800-pound aggregate. The two rates of potassium sulfate gave almost identical increases, however, in the calcium outgo computed as attributable to the limestone supplement. Since related studies have demonstrated that the 2-ton addition of the fine limestone and its dolomite equivalent probably entered the soil complex during the first year (11), the amounts of replaceable calcium subject to the action of the added K_2SO_4 were consequently greater in the soil that that received the liming supplements. More extensive exchange and greater outgo of calcium would, therefore, be expected from the double quantity of K_2SO_4 in the soil systems enriched by sorbed calcium derived from the supplements of limestone and dolomite. When acting upon increased amounts of calcium supplied by the limestone and the dolomite, the double K_2SO_4 additions did increase the outgo of calcium above that induced by the 400-pound additions, but the double additions also increased by 100 per cent the outgo of calcium from the control, and there was, therefore, no net increase in outgo of calcium from the liming treatments. Hence, when acting *solely* upon native supplies of soluble and exchangeable forms of calcium, the double additions of K_2SO_4 were doubly effective in causing a limited exchange of K for Ca. When the native supplies of replaceable Ca had been augmented, however, by the sorbed Ca derived from either of the two liming materials, the double additions of potassium sulfate fell far short of exerting their potential capacity to effect exchange reactions with the calcium components of the soil.

The actual differences between total calcium outgo from the unsupplemented additions of the sulfates of calcium, magnesium, and potassium, and from the same three sulfates with limestone supplements were 1,174, 946, and 1,097 pounds respectively for the 7-year period.

Outgo of magnesium

The magnesium data, in terms of $CaCO_3$, are given in table 4. The total displacement of magnesium by additions of calcium sulfate was only 186 pounds for the 7-year period, or 27 pounds per annum. This replacement was only about one-third of the reciprocal replacement of calcium by the magnesium sulfate treatments (table 3) and was equivalent to only 9 per cent of the potential exchange capacity of the added calcium sulfate. But, the supplement of limestone completely nullified the potential capacity of the added calcium sulfate to replace magnesium and also potassium (table 5).

The recovery of the magnesium from the unsupplemented additions of magnesium sulfate was 60 per cent of the amount added. The effect of the limestone supplement, was to reduce that recovery to 40 per cent of the added

TABLE 4

*Outgo of magnesium as influenced by seven annual equivalent incorporations of sulfates of calcium, magnesium, and potassium**

TANK NUMBER	TREATMENT		MAGNESIUM LEACHED, IN TERMS OF POUNDS $CaCO_3$ PER 2,000,000 POUNDS OF SOIL									
	Annual sulfate additions, in terms of 400 pounds $CaSO_4$ ⇔	Single initial addition ⇔ 2 tons of $CaCO_3$	1930–31	1931–32	1932–33	1933–34	1934–35	1935–36	1936–37	1930–1937		
										Total outgo	Increase	
											Total	Annual
617	Rainwater	None	38	46	67	36	48	47	57	339	.....	...
618	None	None	249	305	217	178	141	162	103	1,355	.....	...
619	$CaSO_4$	None	330	333	245	188	166	168	104	1,534	186	27
20	$CaSO_4$	Limestone	272	270	211	161	154	160	118	1,346	−2	0 [0]†
21	$CaSO_4$	Dolomite	505	510	399	338	256	278	193	2,479	1,131	161 [134]
622	$MgSO_4$	None	390	401	365	332	356	438	295	2,577	1,229	167
23	$MgSO_4$	Limestone	333	242	327	302	304	361	296	2,165	817	117 [−50]
24	$MgSO_4$	Dolomite	608	629	573	381	430	466	361	3,448	2,100	300 [133]
625	K_2SO_4	None	311	344	238	171	140	149	111	1,464	116	17
26	K_2SO_4	Limestone	282	260	213	149	139	148	106	1,297	−51	−7 [0]
27	K_2SO_4	Dolomite	488	604	381	292	260	269	185	2,479	1,131	161 [144]
628	$2 \times K_2SO_4$	None	343	352	277	181	149	148	121	1,571	223	32
29	$2 \times K_2SO_4$	Limestone	335	283	228	159	131	154	104	1,394	46	7 [0]
30	$2 \times K_2SO_4$	Dolomite	599	578	457	223	253	247	176	2,533	1,185	169 [137]
631	None	None	253	301	221	162	138	167	98	1,340	.....	...
632	Rainwater	None	35	42	72	34	37	36	44	300	.....	...
Inches of rainfall.....			38.83	55.33	55.95	38.45‡	61.77	47.23§	52.05	349.6	.....	...

* Total additions of 2,800 pounds and 5,600 pounds $CaSO_4$ or equivalent.

† Bracketed figures show the increases attributable to either limestone or dolomite.

‡ An additional collection of 12.16 inches was made in rain gauges during a period when the tanks were covered.

§ An additional collection of 2.35 inches was made in rain gauges during a period when the tanks were covered.

magnesium. In contrast, the dolomite supplement induced an 871-pound increase in total magnesium outgo. Full recovery of the magnesium supplied as the sulfate was obtained only in its association with the dolomitic supplement and, with the 2,100-pound increase in magnesium outgo, there was a concomitant increase of 693 pounds in calcium outgo.

The replacement-outgo of magnesium induced by the 2,800-pound potassium sulfate treatment was less than 6 per cent of its potential exchange capacity. Again, as in the calcium sulfate series, the limestone supplement nullified the potential capacity of this potassium sulfate treatment to release magnesium, and an exchange of only 46 pounds was registered by the double treatment of 5,600 pounds. The outgo of magnesium induced by the 2,800-pound aggregate of the potassium sulfate additions and its supplement of dolomite was identical with that induced by the equivalent additions of calcium sulfate and dolomite, whereas the additional 2,800-pounds of potassium sulfate induced a further increase of only 54 pounds in magnesium outgo. It is evident that the added potassium ions did not release an equivalence of magnesium, or of calcium, or even of Ca + Mg. This follows also from data of table 5 that show that the maximal retentions of K were only 42 per cent and 36 per cent respectively for the single- and double-rate additions of potassium sulfate.

Influence of the three added sulfates upon the Ca:Mg ratio in leachings

The Ca:Mg ratio in the leachates from the untreated soil was 2.25 to 1. In the total Ca + Mg outgo of 5,882 pounds of $CaCO_3$-equivalence from the unsupplemented calcium sulfate additions, the ratio of Ca to Mg was 2.8:1. For the total Ca + Mg outgo of 6,868 pounds from the $CaSO_4$+ limestone treatment, the Ca:Mg ratio was 4.1:1, as against 1.8:1 for the 6,829-pound total outgo of Ca + Mg from the calcium sulfate and its dolomitic supplement.

Since the outgo of magnesium from the combination treatment of calcium sulfate and limestone was the same as the magnesium outgo from the untreated soil, the enhancement of 2,486 pounds in outgo of calcium alone from that combination was identical to the enhancement in outgo of Ca + Mg. The enhanced outgo of Ca + Mg for the corresponding calcium sulfate + dolomite system was 2,447 pounds, of which 54 per cent was accounted for by calcium and 46 per cent by magnesium.

For the magnesium sulfate series, the Ca:Mg ratio obtained in the 6,158-pound total outgo from the unsupplemented sulfate was 1.4:1. It was 2.1:1 in the 6,692-pound total outgo from the magnesium sulfate with the limestone supplement, and it was 1.1:1 in the 7,175-pound total outgo from the combination treatments of magnesium sulfate and dolomite. The Ca:Mg relationships for the enhancements in outgo induced by the magnesium sulfate in the limestone and dolomite systems were, therefore, 1.8:1 and 1:3 respectively.

The supplements of both limestone and dolomite caused increases of approximately 1,000 pounds in the outgo of Ca + Mg from the calcium sulfate treatment. The dolomitic limestone also increased the Ca + Mg outgo approx-

imately 1,000 pounds above that from the unsupplemented magnesium sulfate. Because of the repressive effect of the limestone upon outgo of magnesium, however, the enhancement in Ca + Mg outgo from the magnesium sulfate and its limestone supplement was restricted by about one-half.

In the Ca + Mg outgo of 4,728 pounds and that of 5,275 pounds from the 2,800-pound and 5,600-pound unsupplemented potassium sulfate additions, the respective Ca:Mg ratios were 2.3:1 and 2.4:1. When supplemented with limestone, the two rates of K_2SO_4 gave Ca + Mg outgo totals of 5,767 pounds and 6,201 pounds, in both of which the Ca:Mg ratio was 3.4:1. For the supplements of dolomite, the totals of Ca + Mg outgo from the two rates of K_2SO_4 were 6,002 pounds and 6,225 pounds, with respective Ca:Mg ratios of 1.42:1 and 1.45:1.

The enhancement in Ca + Mg leached from the dolomitic supplement to the seven 400-pound-rate additions of K_2SO_4 was 1,620 pounds, of which calcium and magnesium were responsible for respective fractions of 30 per cent and 70 per cent. Of the total enhancement of 1,843 pounds in Ca + Mg outgo from the seven double-rate K_2SO_4 additions with the dolomitic supplement, Ca and Mg accounted for 36 per cent and 64 per cent, respectively. Although each double potassium sulfate treatment induced some further increases in outgo of Ca + Mg from the liming supplements, the increases were not proportionate to the potential exchange capacity of the double additions.

Outgo of potassium

The potassium contents of the rainwaters and the amounts of K leached, per 2,000,000 pounds of soil, are given in table 5. At the two rates, the potassium sulfate supplied 1,608 pounds and 3,216 pounds of K, or annual additions of 230 pounds and 460 pounds. The accumulation of exchangeable potassic compounds that developed during the previous period of sod culture and the biochemical activities that ensued when the sod-denuded soil was maintained fallow, are reflected by the unusually high concentration of potassium in the leachates from the untreated controls, especially during the initial 2-year period. After years of cultivation, the same type of soil, without potash treatment, yielded only about 5–10 pounds of K per annum to the leachates (5, 13, 18).

Although ground gypsum, or land plaster, is now seldom added as a separate soil treatment, its use has been advocated and practiced in certain sections. It was one of the treatments applied to the Jordan Fertility Plats (3), initiated in 1881. Storer (23, p. 325) stated, "This substance has been used as a fertilizer from time immemorial." He and Patten (21) believed that it effected liberation of soil potash.

None of the three treatments of calcium sulfate, alone and with supplements of limestone and dolomite, caused an increase in the outgo of K from this slightly acidic soil of high content of readily leached K. Nevertheless, a 4,250-pound equivalence of calcium sulfate, engendered within the soil from addi-

tions of ferrous sulfate, did effect a meager release of K from the same type of soil, when more acidic and of depleted exchangeable K content (15). In that experiment, liming materials also completely nullified the potential capacity of the engendered calcium sulfate to effect an exchange for potassium, as reflected by a decrease in the outgo of potassium. It appears, therefore, that additions of calcium and magnesium sulfates *cannot* be depended upon to

TABLE 5

*Outgo of potassium, as influenced by seven annual equivalent incorporations of sulfates of calcium, magnesium, and potassium**

TANK NUMBER	TREATMENT		POTASSIUM LEACHED, IN TERMS OF POUNDS K PER 2,000,000 POUNDS OF SOIL									
	Annual sulfate additions, in terms of 400 pounds $CaSO_4$ ⇔	Single initial addition ⇔ 2 tons of $CaCO_3$	1930-31	1931-32	1932-33	1933-34	1934-35	1935-36	1936-37	1930-1937		
										Total outgo	Increase	
											Total	Annual
617	Rainwater	None	7	5	5	3	5	6	6	37	.....	...
618	None	None	103	107	74	41	55	45	24	449	.....	...
619	$CaSO_4$	None	114	106	72	35	55	45	24	451	−8	−1
20	$CaSO_4$	Limestone	106	104	66	32	52	45	27	432	−27	−4
21	$CaSO_4$	Dolomite	93	104	62	34	47	48	27	415	−44	−6
622	$MgSO_4$	None	112	110	76	35	54	45	27	459	0	0
23	$MgSO_4$	Limestone	105	91	65	34	45	56	27	423	−36	−5
24	$MgSO_4$	Dolomite	104	105	68	29	46	46	27	425	−34	−5
625	K_2SO_4	None	160	235	273	149	255	253	184	1,509	1,050	150
26	K_2SO_4	Limestone	151	191	231	137	249	255	191	1,405	946	135
27	K_2SO_4	Dolomite	135	220	232	145	217	263	180	1,392	933	133
628	$2 \times K_2SO_4$	None	247	376	386	341	484	466	342	2,642	2,183	312
29.	$2 \times K_2SO_4$	Limestone	260	313	402	304	443	456	354	2,532	2,073	296
30	$2 \times K_2SO_4$	Dolomite	245	354	430	249	466	457	369	2,570	2,111	302
631	None	None	98	106	89	43	53	54	26	469	.....	...
632	Rainwater	None	6	5	5	4	5	5	5	35	.....	...
Inches of rainfall.....			38.83	55.33	55.95	38.45†	61.77	47.23‡	52.05	349.6	.....	...

* Total additions of 2,800 pounds and 5,600 pounds $CaSO_4$ or equivalent.

† An additional collection of 12.46 inches was made in rain gauges during a period when the tanks were covered.

‡ An additional collection of 3.25 inches was made in rain gauges during a period when the tanks were covered.

effect an enrichment in supplies of nutrient potassium by direct chemical reactions, especially on either naturally calcareous or limed soils.

Taken in connection with the results of table 2, the data of table 5 show that the additions of potassium sulfate were leached mainly in that form. The increases in the amounts of K leached from the unsupplemented 2,800-pound and 5,600-pound $CaSO_4$-equivalent additions of potassium sulfate were 65 and

68 per cent of the respective amounts incorporated. The recoveries of K from the two corresponding cumulative additions of potassium sulfate with limestone supplements were 59 per cent and 64 per cent, whereas respective K recoveries of 58 per cent and 66 per cent were obtained when dolomitic supplements were used. For additions of potassium sulfate at both rates, the outgo of potassium was therefore decreased somewhat by both types of lime-

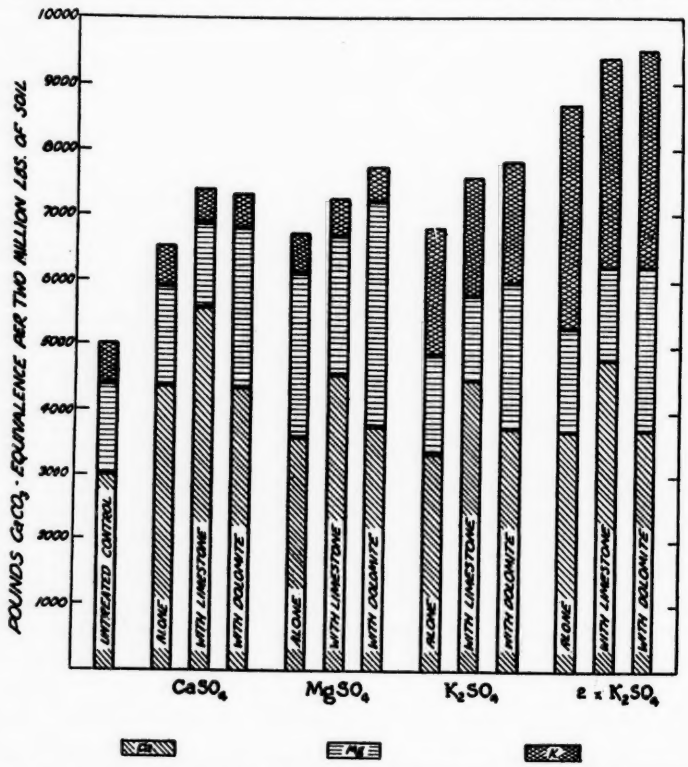

FIG. 1. OUTGO OF CALCIUM, MAGNESIUM, AND POTASSIUM FROM A SOD-SKIMMED SOIL TREATED WITH SEVEN ANNUAL EQUIVALENT INCORPORATIONS OF SULFATES OF CALCIUM, MAGNESIUM, AND POTASSIUM, WITH AND WITHOUT A SINGLE INITIAL ADDITION OF EITHER LIMESTONE OR DOLOMITE

stone. It has been shown that the repressive effect exerted by liming materials upon K outgo is much more pronounced when light additions of K are made (9).

Outgo of total bases induced by the three sulfates

The results of table 6 show the respective aggregates for outgo of "total bases"—calcium, magnesium, and potassium. To allow direct additive values, in terms of pounds per 2,000,000 pounds of soil in this table outgo of

potassium was computed to the $CaCO_3$-equivalence values, as was done for the outgo of calcium and of magnesium in tables 3 and 4, respectively.

The $CaCO_3$-equivalence of the aggregate of the seven additions of each of the three sulfates at the 400-pound rate was 2,059 pounds. The SO_4 data of table 2 showed that the SO_4 recoveries from the three sulfates were in the range of 93–100 per cent. A cation build-up from each of the sulfates occurred, since the enhancements in outgo of total bases from the unsupplemented additions of calcium and magnesium sulfates, and also of potassium sulfate at

TABLE 6

Effect of calcium, magnesium, and potassium sulfate treatments, with and without limestone and dolomite, on total bases leached during the 7-year period*

TANK NUMBER	TREATMENT		Ca, Mg, AND K, EXPRESSED AS $CaCO_3$ ⇔, POUNDS PER 2,000,000 POUNDS OF SOIL				
	Annual sulfate additions, in terms of 400 pounds $CaSO_4$ ⇔	Single initial additions ⇔ 2 tons of $CaCO_3$	Calcium	Magnesium	Potassium	Aggregate	Increase†
618	None	None	3,147	1,355	575	5,077	.....
619	$CaSO_4$	None	4,348	1,534	577	6,459	1,490
20	$CaSO_4$	Limestone	5,522	1,346	553	7,421	2,452
21	$CaSO_4$	Dolomite	4,350	2,479	531	7,360	2,391
622	$MgSO_4$	None	3,581	2,577	588	6,746	1,777
23	$MgSO_4$	Limestone	4,527	2,165	541	7,233	2,264
24	$MgSO_4$	Dolomite	3,727	3,448	544	7,719	2,750
625	K_2SO_4	None	3,364	1,464	1,932	6,760	1,791
26	K_2SO_4	Limestone	4,461	1,297	1,798	7,556	2,587
27	K_2SO_4	Dolomite	3,523	2,479	1,782	7,784	2,815
628	$2 \times K_2SO_4$	None	3,704	1,571	3,382	8,657	3,688
29	$2 \times K_2SO_4$	Limestone	4,807	1,394	3,241	9,442	4,473
30	$2 \times K_2SO_4$	Dolomite	3,692	2,533	3,290	9,515	4,546
631	None	None	2,920	1,340	600	4,860	.....

* Related studies had demonstrated that the outgo of sodium native to the soil was so nugatory as to warrant its exclusion in the present study.

† By subtraction of mean outgo from controls, as result of a total rainfall of 349.6 inches.

both rates, were less than the respective $CaCO_3$-equivalences of the added sulfates. The enhancement in outgo of total bases from each limed unit was, however, in excess of the equivalence of the base carried by its companion sulfate treatment. In general, the greater solubility and mobility of the incorporations of magnesium sulfate was in evidence.

The effect of residues of liming materials on conservation of subsequent additions of potassium sulfate

In the study from which the data of tables 1–6 were obtained, the maximal effect of the full-depth incorporations of limestone and of dolomite were brought to bear upon soil naturally rich in readily soluble native salts, augmented by the annual incorporations of sulfates. In another and older lysim-

eter experiment, the outgo of sulfates induced by 2,000-pound CaO-equivalent-rate additions of limestone, dolomite, burnt lime, and magnesia had been determined for a 12-year period (17). The two oxides had also been incorporated at the 3,750-pound rate.

Beginning with the thirteenth year after the liming treatments, annual surface additions of an aqueous solution of potassium sulfate were made to the fallow soils. These additions brought an annual supply of 68 pounds of sulfate sulfur. Certain units had also received single additions of sulfur, as ferrous sulfate, as pyrite, and as elemental sulfur, at the rate of 1,000 pounds of S. The balance between sulfur increment and outgo was reported in terms of S (15), and that expression is therefore continued in the data of table 7. The fate of the potassium supplied by the eight annual additions of potassium sulfate and the correlary record of outgo of Ca and Mg have been presented in a recent contribution (18). Since the fate of the SO_4 radical of added sulfates is a primary consideration of the present paper, the reciprocal relationships between Ca, Mg, and K of the 20-year study will not be considered.

The data of table 7 show the accelerative effects of the several liming treatments upon total sulfate sulfur outgo during the initial 12-year period, 1917–1929, that preceded the 8-year period of annual additions of potassium sulfate. The magnesic materials were more accelerative than the calcic materials upon sulfate outgo. These increases of the initial 12-year period are attributable either to greater quantities of engendered sulfates, or to a change in soil structure that admitted of a more ready leaching of sulfates from a common supply of soil sulfates and rain water and atmospheric increments, or to combinations of these causes. Since the initial accelerative effect of the liming treatments had been diminished by the end of the twelth year, the continued effect exerted by the residues of the liming materials upon retention of the added sulfates is probably due to altered capacities of the soils to retain sulfates.

Without exception, the amount of sulfate sulfur leached during the final 8-year period was greater than the 544-pound supply of S furnished solely by the eight additions of potassium sulfate. An additional common 326-pound increment from rain water, however, cannot be disregarded. Hence, each sulfate outgo was less than the amount of sulfates that entered the soil during the last 8 years.

The total amount of S leached from the unlimed soil was 79 per cent of the total increment from additions and rain water. Each liming treatment caused an enhancement in sulfate outgo within the range of 83 to 87 per cent of the common total increment. The enhancements in sulfate outgo attributable to the several liming materials were in the range of 6 to 14 per cent of the uniform amount of SO_4 supplied by the eight annual additions of potassium sulfate, the magnesic materials being somewhat more accelerative than the calcic materials.

As noted, the accelerative effect that the liming materials exerted upon sulfofication was most noticeable during the early years and had been sub-

TABLE 7

Outgo of sulfate sulfur induced by liming treatments and by subsequent annual additions of potassium sulfate from a clay loam during a 20-year period*

TANK NUMBER	FULL DEPTH SINGLE INCORPORATION 1917	OUTGO OF SULFATES, AS POUNDS S PER 2,000,000 POUNDS OF SOIL												
		No sulfates added, period 1917–1929		From 8 annual additions of 200 pounds K_2SO_4, 1929–1937										
		Actual outgo	Increase from soil, due to liming treatment	1929–30	1930–31	1931–32	1932–33	1933–34	1934–35	1935–36	1936–37	Total outgo		Enhanced outgo, induced by liming treatments	
												Pounds	As per cent of increment†	Pounds	As per cent of added K_2SO_4
50	None	405	...	63	55	114	97	67	104	109	76	685	79	..	..
51	Limestone‡	472	67	78	75	108	97	77	109	96	78	718	83	33	6
52	Dolomite‡	507	102	84	75	114	96	78	108	102	89	746	86	61	11
53	Burnt lime‡	503	98	80	70	117	94	77	105	102	90	735	84	50	9
54	Burnt lime§	524	119	87	82	110	93	84	98	101	91	746	86	61	11
55	MgO‡	494	89	85	72	115	92	77	104	100	91	736	84	51	9
56	MgO§	536	131	92	88	112	91	87	100	99	92	761	87	76	14

* Annual surface application, by solution, at the rate of 200 pounds K_2O per 2,000,000 pounds of soil, gave an annual S increment of 68 pounds.

† Total of 870 pounds, accounted for by 326 pounds from rain water and 544 pounds from K_2SO_4.

‡ Single incorporation at rate of 2,000 pounds CaO per 2,000,000 pounds of soil.

§ Single incorporation at rate of 3,750 pounds CaO per 2,000,000 pounds of soil.

stantially diminished prior to the beginning of the thirteenth year, when the supplemental annual additions of K_2SO_4 were begun. The possibility of losses of sulfur through desulfofication has been deemed negligible, because of the inherent oxidative capacity of the soil for additions of elemental sulfur, pyrite, and sphalerite. Any decrease in the sulfur content of a fallow soil is therefore deemed attributable solely to the leaching of sulfates. It appears, therefore, that the greater outgo of sulfates induced by the several liming materials during the final 8-year period was due primarily to the residual effects of the liming materials in accelerating the outgo of moderate incorporations of sulfates, or in diminishing the capacity of the soil to retain the sulfates.

Emphasis should be given to the fact that the data of table 7 were obtained by the use of the silty clay loam after its depletion by cultural cropping, whereas the data of the first six tables relate to an unusual outgo of nutrients from a similar soil of high fertility resultant from an extended period in sod.

Application of the findings as to sulfates

The results indicate that the ordinary incorporations of fertilizer sulfates will not accomplish a material build-up of the sulfur content of fallow soils. To effect such a build-up, it would seem necessary that the soil be supplied with continuous additions of substantial quantities of sulfates, as supplemental to appreciable increments of rain water and atmospheric sulfates. Such increments decrease in areas remote from urban and coal-consuming centers. Moreover, the possibility of a build-up of sulfate supplies in sandy types of soil would also be much less than in the case of the heavier type of silty clay loam used in the present study. The leaching of sulfates from light sandy soils of low organic matter content would undoubtedly be more rapid and more extensive than that shown for the heavier soils of the present study, and exchange reactions would be less extensive.

In cropped soils, the proportions of rain water leached would be decreased, and the uptake of sulfates by the growing plant would also diminish the amounts of sulfates that would otherwise go out in the leachings. Some of the sulfates used by the plants would also be returned to the soils by root residues. In some localities, rain water sulfur may be appreciable, but it is probable that primary dependence for the conservation of supplies of sulfur must rest upon organic reserves.

It is also apparent that the leachings of sulfates from ordinary additions of calcium and magnesium sulfates will be substantially in the form applied, although some interchange is induced by the cation of the added sulfate, in the absence of liming supplements. The calcium sulfate additions did cause a 27-pound per annum depletion in the magnesium content of the soil; but, this effect was nullified by supplements of high-calcic limestone. The magnesium sulfate additions caused a 78-pound calcium replacement per annum. Neither calcium sulfate nor magnesium sulfate was capable of increasing the outgo of potassium.

The continued additions of potassium sulfate enhanced the quantities of both calcium and magnesium in the free soil-water. Such enhancements were, however, only fractions of the potential exchange capacities of the additions, the larger part of the added potassium sulfate being leached in that form.

SUMMARY

A 7-year lysimeter study was conducted with a fertile brown silty clay loam to determine the fate of equivalent annual additions of SO_4 in combinations with Ca, Mg, and K, and interchange between those cations, with and without single initial supplements of limestone and of dolomite.

Sulfate recoveries of 93 to 100 per cent were obtained, with complete recoveries only from the additions of magnesium and potassium sulfates with dolomitic supplements. Neither limestone nor dolomite caused decreases in SO_4 outgo.

The maximal outgo of calcium from the unsupplemented sulfates was from the calcium sulfate, about two-thirds of the aggregate addition being recovered. Some increase in calcium outgo was induced by magnesium sulfate and also by potassium sulfate at two rates. The four limestone supplements caused increases of about 150 pounds of $CaCO_3$ in annual outgo; the four dolomite supplements induced either meager enhancements or none.

The largest outgo of magnesium from the unlimed units was about 60 per cent of the additions as magnesium sulfate, with small increases attributable to the sulfates of calcium and potassium. A uniform increase of about 125 pounds of magnesium, in terms of $CaCO_3$, was caused by the supplements of dolomite, whereas the outgo of magnesium from each supplement of limestone was less than the outgo from its unlimed control.

The effects of the sulfates of calcium and magnesium, alone and with supplements of limestone and dolomite, on Ca:Mg ratios were noted.

Neither calcium nor magnesium sulfate caused any increase in outgo of potassium from this soil of unusually high content of exchangeable K, whereas both limestone and dolomite repressed the outgo of that element from soil alone and also from the soil treated with potassium sulfate.

Comparisons of outgo of total bases showed that each sulfate treatment caused a cation build-up.

Each indicated interchange induced by the aggregate of the seven annual additions of sulfates was but a small fraction of the potential exchange capacity of the added sulfate.

Another similar soil, of depleted potassium content, that had been limed 12 years previously was used to determine the residual effect of calcic and magnesic materials upon the conservation of SO_4 from eight annual additions of potassium sulfate. No recovery was equal to the amount added, but an increase in sulfate outgo was induced by each of six liming treatments.

The findings were considered in their relation to the problem of nutrient sulfur in soils of the humid region.

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INFLUENCE OF SALTS AND SOIL-WATER RATIO ON pH VALUE OF SOILS

AMAR NATH PURI AND A. G. ASGHAR

Irrigation Research Institute, Lahore, India

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The influence of salts and of the soil-water ratio on soil reaction has been studied by several workers, notably Crowther (2), Bülmann and Jensen (1), and Pierre (3). The general conclusion is that salts depress the pH value, but the magnitude of this effect has not been studied systematically. The conclusion that a twofold dilution causes an increase of 0.1 in pH, so that a 1:5 ratio will have a pH value about 0.25 higher than that of a 1:2 ratio (2), must be considered with reference to the type of soils studied. As a matter of fact, no such simple relationship has so far been discovered to be universal. When diluted, some soils show a marked increase in pH, and others show hardly any change. A closer study of the literature reveals the need for further elucidation to explain the apparent contradictions and discrepances in the results.

Since the pH value of soil is due to the surface ionization of the colloidal particles and hydrolysis of the exchangeable base, it is reasonable to suppose that the presence of a salt (common ion) would reduce hydrolysis and result in a lowering of the pH value. On the other hand, since the ionization is confined to the surface, mere dilution in the absence of salts may have no marked effect on the pH value of the suspension as a whole. The object of this paper is to describe the experimental evidence brought forth in support of this contention.

PREPARATION OF THE SOIL

A black cotton soil of high clay content and base exchange capacity was made unsaturated with respect to bases by exhaustive leaching with 0.05 *N* HCl until free from exchangeable Ca, followed by leaching with distilled water until free from Cl ions. The acid-treated soil was neutralized with different bases, so that soils with increasing pH values containing known amounts of exchangeable bases were obtained. The effect of salts and soil-water ratio was studied on these soils. The pH values were determined by the glass electrode using the Cambridge electrometer valve combined potentiometer and pH meter.

EFFECT OF SOIL-WATER RATIO

The results of the study of the effect of soil-water ratio, given in table 1, show that the same pH is obtained for a given soil even when the soil-water

ratio is varied from 1:5 to 1:25. Erratic values occur here and there, but they do not in any way affect the general conclusion that even a fivefold dilution has virtually no effect on soil reaction. It is noteworthy that other workers have found that the effect of soil-water ratio is greatly reduced in

TABLE 1

Effect of soil-water ratio on pH of single-base soils

SOIL-WATER RATIO	1	2	3	4	5	6
			pH values of Na-soil			
1:5	5.70	8.44	9.18	9.94	10.36	....
1:6	5.64	8.42	9.16	9.83	10.38	....
1:7	5.63	8.43	9.14	9.75	10.34	....
1:8	5.63	8.42	9.16	9.76	10.38	....
1:10	5.63	8.43	9.22	9.79	10.38	....
1:12	5.63	8.40	9.16	9.82	10.38	....
1:14	5.63	8.71	9.11	9.80	10.40	....
1:19	5.66	8.48	9.19	9.85	10.39	....
1:25	5.81	8.48	9.18	9.87	10.38	....
			pH values of K-soil			
1:5	4.80	6.06	7.40	8.81	9.29	9.86
1:6	4.50	5.68	7.28	8.70	9.44	9.88
1:7	4.50	5.69	7.08	8.72	9.44	9.86
1:8	4.50	5.66	7.10	8.67	9.48	9.87
1:10	4.50	5.69	7.13	....	9.41	9.90
1:12	4.50	5.71	7.28	....	9.48	9.90
1:14	4.58	5.69	7.15	....	9.50	9.94
1:19	4.58	5.71	7.37	8.56	9.50	10.00
1:25	4.80	5.70	7.68	8.86	9.56	9.98
			pH values of Ca-soil			
1:5	4.62	5.26	5.64	6.25	7.10	8.75
1:6	4.59	5.22	5.60	6.24	7.14	8.73
1:7	4.53	5.23	5.62	6.26	7.13	8.62
1:8	4.53	5.20	5.60	6.26	7.11	8.62
1:10	4.64	5.27	5.62	6.28	7.12	8.59
1:12	4.70	5.23	5.61	6.29	7.14	8.69
1:14	4.85	5.24	5.64	6.26	7.18	8.60
1:19	4.82	5.21	5.64	6.34	7.11	8.56
1:25	4.86	5.30	5.62	6.33	7.16	8.58

magnitude when the soil is leached with water and redispersed after most of the soluble salts have been removed (1). The results with soils neutralized to higher pH values are of interest, because in these soils a certain amount of hydrolysis might be expected as a result of dilution, but even in these soils the effect of dilution is not noticeable. Apparently the pH value is governed

entirely by the nature and amount of exchangeable base, and no appreciable quantity of metallic hydroxide is present even at pH 10 in these mixtures.

EFFECT OF SALTS

The effect of salts was studied by using chlorides of various ions, the corresponding metallic chloride being used for every exchangeable base. Ten-gram portions of soils at different pH values were suspended in 50 cc. of water, and normal solutions of the corresponding chlorides were added in 1-cc. lots up to 50 cc. The addition of these solutions undoubtedly caused some dilution of the suspension, but as we have seen that dilution alone has no effect on pH, this was ignored. It was also ascertained by direct experiment that results are substantially the same when increasing quantities of salts in the solid state are added.

The results for Na, K, and Ca are given in table 2, and those for Mg, Ba, Sr, and Li are plotted in figure 1. All the curves obtained are similar, and, therefore, only a few are given by way of illustration. An initial rapid fall is followed by a more gradual one. The initial fall is greater in the acid range and becomes less when the pH is high. When the curves are plotted on a semilogarithmic scale; that is, pH values against log concentration of salt, we get a series of parallel straight lines, the slope of which is characteristic of the basic radical. The following relations are found to hold for various soils:

$$\mathrm{pH} = \mathrm{pH}_0 - K \log C$$

where pH is the initial pH without any salt; C is the concentration of the salt in milliequivalents per 100 gm. of soil; and K is a constant, characteristic of the basic ion.

The values of K for various ions are as follows: Li = 0.30, Na = 0.79, K = 0.55, Ca = 0.48, Mg = 0.48, Ba = 0.26, Sr = 0.28.

It is to be remembered that the effect of salts in lowering the pH values of soils is analogous to a similar effect in ordinary buffer solution. Thus it can be shown that the pH value of sodium carbonate-bicarbonate mixture is less in the presence of KCl than in its absence (4).

A closer study of these results presents some interesting aspects which would offer a rational explanation of the discrepancies observed by previous workers in the effect of soil-water ratio on pH values. It is clear that in the steeper portion of the curve a very small concentration of salts such as would be ordinarily found in most of the normal soils would materially alter the pH value. Since this effect does not depend on the absolute quantity of the salt, but rather on its concentration in a suspension, dilution will have the effect of raising the pH value, and the magnitude of this change will be governed entirely by the nature and quantity of the salt present in the soil. These results also lead to the conclusion that measurement of the pH values of soils in N KCl solution would give more reproducible results in the hands of different workers, for not only would the effect of soil-water ratio be negligible,

TABLE 2

Effect of salts on pH value of single-base soils

CC. OF *N* SOLUTION ADDED TO 50 CC. OF SUSPENTION	1	2	3	4	5	6	7
			NaCl added to Na-soil				
0	5.69	6.84	8.44	9.43	10.00	10.37	....
1	5.63	5.91	7.68	9.90	9.52	10.10	....
2	5.38	5.62	7.49	8.79	9.38	10.00	....
3	5.22	5.46	7.32	8.64	9.30	9.94	....
4	4.13	5.34	7.22	8.57	9.22	9.86	....
5	4.05	5.23	7.15	8.53	9.18	9.83	....
6	3.94	5.18	7.10	8.46	9.12	9.80	....
7	3.91	5.11	7.00	8.41	9.11	9.78	....
8	3.86	5.08	6.95	8.36	9.09	9.70	....
9	3.82	4.99	6.88	8.29	9.02	9.71	....
10	3.82	4.98	6.84	8.24	9.00	9.68	....
15	3.72	4.88	6.77	8.16	8.92	9.60	....
20	3.64	4.80	6.66	8.08	8.85	9.53	....
25	3.60	4.74	6.65	8.02	8.78	9.52	....
30	3.57	4.70	6.58	8.00	8.75	9.44	....
35	3.56	4.66	6.54	7.93	8.73	9.41	....
40	3.56	4.66	6.50	7.92	8.65	9.37	....
50	3.55	4.62	6.48	7.86	8.59	9.34	....
Total change....	2.14	2.22	1.96	1.57	1.41	1.03	....
			$CaCl_2$ added to Ca-soil				
0	4.48	4.95	5.96	7.36	7.94	8.26	8.59
1	3.34	3.80	4.73	6.74	7.14	7.72	7.88
2	3.23	3.71	4.51	6.56	6.95	7.55	7.68
3	3.22	3.60	4.44	6.47	6.86	7.49	7.64
4	3.16	3.56	4.32	6.40	6.89	7.44	7.55
5	3.15	3.50	4.30	6.38	6.90	7.40	7.54
6	3.13	3.49	4.26	6.33	6.90	7.36	7.49
7	3.12	3.51	4.24	6.25	6.85	7.33	7.46
8	3.10	3.49	4.20	6.25	6.82	7.32	7.41
9	3.08	3.49	4.20	6.22	6.78	7.30	7.38
10	3.13	3.49	4.18	6.24	6.76	7.27	7.38
15	3.10	3.44	4.14	6.12	6.68	7.21	7.30
20	3.08	3.42	4.13	6.08	6.62	7.16	7.30
25	3.08	3.44	4.10	6.08	6.58	7.15	7.25
30	3.14	3.43	4.08	6.00	6.50	7.14	7.29
35	3.14	3.43	4.08	6.00	6.50	7.06	7.20
40	3.16	3.43	4.08	5.97	6.50	7.02	7.18
50	3.16	3.41	4.08	5.93	6.46	7.04	7.16
Total change....	1.32	1.54	1.88	1.43	1.48	1.22	1.43

TABLE 2—*Concluded*

CC. OF *N* SOLUTION ADDED TO 50 CC. OF SUSPENTION	1	2	3	4	5	6	7
			KCl added to K-soil				
0	5.09	5.98	7.40	8.90	9.35	10.02	....
1	4.31	5.47	7.06	8.38	9.04	9.81	....
2	4.04	5.29	6.92	8.26	8.91	9.74	....
3	3.83	5.16	6.82	8.08	8.87	9.65	....
4	3.74	5.06	6.70	7.94	8.82	9.62	....
5	3.64	4.96	6.64	7.78	8.73	9.52	....
6	3.60	4.86	6.62	7.78	8.72	9.50	....
7	3.55	4.82	6.62	7.78	8.63	9.48	....
8	3.51	4.76	6.54	7.70	8.61	9.48	....
9	3.46	4.73	6.48	7.67	8.57	9.42	....
10	3.46	4.70	6.42	7.61	8.54	9.40	....
15	3.46	4.62	6.41	7.51	8.47	9.34	....
20	3.41	4.55	6.37	7.46	8.42	9.24	....
25	3.42	4.53	6.32	7.42	8.35	9.19	....
30	3.42	4.49	6.30	7.38	8.29	9.17	....
35	3.42	4.45	6.28	7.35	8.27	9.16	....
40	3.42	4.42	6.20	7.30	8.25	9.12	....
50	3.42	4.38	6.18	7.27	8.23	9.12	....
Total.....	1.67	1.60	1.22	1.63	1.12	0.90	....

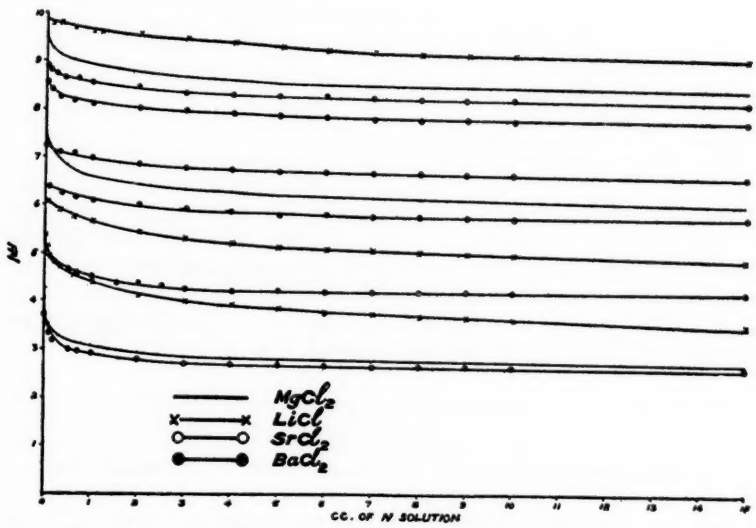

FIG. 1. EFFECT OF MAGNESIUM, LITHIUM, STRONTIUM, AND BARIUM CHLORIDES ON THE pH VALUES OF THEIR CORRESPONDING SOILS

but day by day variations in natural soils which are obviously due to changes in salt content would disappear and the pH value of a soil would assume the importance of a fundamental constant. In order to determine whether the general conclusions reached for this soil are applicable to other soils, 10 soils were taken. These soils were first made unsaturated by 0.05 *N* HCl treatment and then brought to a pH between 6 and 7 by the addition of KOH. The effect of increasing amounts of KCl was studied on these soils. The results when plotted on a semilogarithmic scale, i.e., pH against log concentration, give a series of parallel lines. In table 3 are given the pH values of the K-soils both in water and in *N* KCl. The difference, in general, is of the order of 2.

Since the presence of salts depresses the pH value of soil, leaching should result in a rise in the pH value. This has been noticed by other workers. To study the effect in greater detail, 20 soils were leached first with water

TABLE 3

The pH values of K-soils at two different pH levels in water and in N *KCl*

SOIL NUMBER	pH			pH		
	In water	In *N* KCL	Difference	In water	In *N* KCL	Difference
M1.....	8.34	6.36	1.98	6.00	3.88	2.12
M2.....	8.23	6.14	2.09	6.35	4.48	1.87
M5.....	7.23	5.54	1.69	5.84	4.00	1.84
M6.....	7.40	5.31	2.09	5.50	3.64	1.86
M9.....	7.98	6.13	1.85	6.43	4.53	1.90
M12.....	7.63	5.85	1.78	5.86	3.90	1.96
M15.....	9.14	6.99	2.15	....	....	....
M23.....	8.27	6.18	2.09	....	....	....
P.C. 7.....	6.92	4.56	2.36	....	....	....
P.C. 15.....	6.24	4.58	1.66	....	....	....

then with alcohol, and dried. The purpose of the final leaching with alcohol was to facilitate drying and removal from the filter paper. The washed soils were suspended in water, and the pH values were determined in the usual way, both in water and in *N* KCl. The pH values of the original soils in water and in *N* KCl were also determined. The results are given in table 4, from which the following conclusions may be drawn:

The pH value of the leached soil is always higher than that of the unleached soil.

This difference becomes inappreciable when pH is determined in *N* KCl.

The effect of KCl in lowering the pH value is greater in the leached than in the original soil.

The difference between the change in pH value due to KCl in the leached and in the unleached soil is of the same order as the rise in pH value of the original soil due to leaching.

It will be seen that the discrepancies in the literature regarding the effect of soil-water ratio on reaction are satisfactorily explained by the fact that

salts lower the pH value of soils. The fact that soil reaction shows rapid fluctuations can also be understood, since it is associated with changes in the salt content of the soil. It is also clear that the pH value determined in *N* KCl will not be subject to rapid changes, and such a value could be used as a fundamental constant for the soil. The pH values in *N* KCl are easily determined both colorimetrically and electrometrically and will show much greater consistency in the hands of different workers than will pH values

TABLE 4

Effect of washing and of KCl on soil reaction

SOIL NUMBER	CLAY	pH VALUES*							
		W	WK	d	U	UK	d′	(W-U)	(d-d′)
	per cent								
P.C. 1.....	11.3	8.86	8.07	0.79	8.07	7.90	0.17	0.79	0.62
P.C. 2.....	59.3	9.18	7.24	1.94	8.24	7.12	1.12	0.94	0.82
P.C. 3.....	62.2	7.72	6.18	1.54	7.61	6.34	1.27	0.11	0.27
P.C. 4.....	15.2	8.89	7.37	1.52	8.16	7.74	0.42	0.73	1.10
P.C. 5.....	12.3	8.89	8.00	0.89	8.34	7.84	0.50	0.55	0.39
P.C. 6.....	28.4	5.99	4.31	1.68	5.18	4.18	1.00	0.81	0.68
P.C. 7.....	21.8	9.86	8.38	1.48	9.50	8.62	0.88	0.36	0.60
P.C. 8.....	25.2	8.66	7.46	1.20	8.28	7.40	0.88	0.38	0.32
P.C. 9.....	21.6	6.66	5.09	1.57	5.70	4.83	0.87	0.96	0.70
P.C. 10.....	35.6	9.11	7.43	1.68	8.54	7.50	1.04	0.57	0.64
P.C. 11.....	32.8	8.86	7.42	1.44	8.40	7.36	1.04	0.46	0.40
P.C. 12.....	7.2	6.43	4.88	1.55	5.24	4.58	0.66	1.19	0.89
P.C. 13.....	58.9	8.79	7.27	1.52	8.32	6.96	1.36	0.47	0.16
P.C. 14.....	21.5	6.14	4.66	1.48	5.48	4.52	0.96	0.66	0.52
P.C. 15.....	22.4	8.47	7.71	0.76	7.66	7.58	0.08	0.81	0.68
P.C. 16.....	8.7	8.88	8.17	0.71	8.39	8.08	0.31	0.49	0.40
P.C. 17.....	14.1	8.64	7.66	0.98	7.82	7.58	0.24	0.82	0.74
P.C. 19.....	42.3	8.77	7.44	1.33	8.14	7.24	0.90	0.63	0.43
P.C. 21.....	13.5	9.12	7.38	1.74	8.17	7.45	0.72	0.95	1.02

* W = pH value of washed soil in water.
WK = pH value of washed soil in *N* KCl.
U = pH value of original soil in water.
UK = pH value of original soil in *N* KCl.
d = W − WK.
d′ = U − UK.

in water. The effect of soil-water ratio is also inappreciable when pH values are determined in *N* KCl. This will be seen from table 5.

Some difficulty undoubtedly will be experienced in the interpretation of results by those who are used to determining pH values in water suspensions; but this difficulty will disappear when it is remembered that the pH values of washed soil in *N* KCl solution are in the majority of cases lower by approximately 1.5 than those in water suspension. This fact would be found helpful

for the mental adjustment in the initial stages. It may even be desirable to determine the pH value both in water and in *N* KCl for some time as is the custom in certain soil laboratories, but it must be remembered that whereas the pH in water is partly arbitrary and likely to fluctuate from day to day, the pH value in *N* KCl is more closely related to the state of saturation of the exchange complex in the soil, which will not change in comparatively short intervals of time. Many workers prefer the use of *N* KCl for determining soil reaction, and the present work offers a rational explanation for this preference.

TABLE 5

Effect of soil-water ratio on the reaction of noncalcareous soils in water and in N *KCl*

SOIL-WATER RATIO	P.C. 3		P.C. 4		P.C. 6		P.C. 8		P.C. 9		P.C. 10	
	KCL	Water	KCL	Water	KCL	Water	KCL	Water	KCL	Water	KCL	Water
1:2.5	6.18	7.57	7.62	8.26	4.20	5.35	7.14	8.42	4.86	5.85	7.22	8.48
1:5	6.22	9.83	7.62	8.42	4.26	5.55	7.14	8.66	4.86	5.99	7.20	8.78
1:7	6.22	7.95	7.62	8.42	4.30	5.58	7.19	8.72	4.88	6.02	7.19	8.82
1:8	6.24	8.06	7.62	8.45	4.32	5.58	7.21	8.72	4.90	6.08	7.20	8.86
1:10	6.25	8.16	7.62	8.52	4.33	5.60	7.22	8.76	4.90	6.08	7.32	8.96
1:12	6.26	8.26	7.63	8.51	4.34	5.64	7.14	8.76	4.93	6.11	7.42	9.01
1:14	6.25	8.26	7.63	8.52	4.39	5.61	7.22	8.76	4.92	6.14	7.42	9.05
1:19	6.14	8.46	7.63	8.56	4.39	5.71	7.21	8.80	4.92	6.17	7.42	9.11
1:25	6.18	8.46	7.55	8.58	4.42	5.79	7.05	8.80	4.93	6.23	7.40	9.21

TABLE 6

Effect of soil-water ratio on the reaction of calcareous soils in N *KCl*

SOIL-WATER RATIO	NON-CALCAREOUS SOILS PLUS $CaCO_3$						NATURALLY CALCAREOUS SOILS			
	P.C. 3	P.C. 4	P.C. 6	P.C. 8	P.C. 9	P.C. 10	1	2	5	7
1:2.5	6.62	7.62	7.62	6.76	6.92	7.27	7.9	6.95	7.80	8.60
1:5	6.63	7.73	6.84	6.84	7.03	7.43	8.12	7.10	7.94	8.80
1:7	6.72	7.84	7.05	7.84	7.06	7.53	8.22	7.18	8.13	8.92
1:8	6.79	8.00	7.18	7.88	7.22	7.64	8.39	7.32	8.25	8.99
1:10	6.90	8.03	7.22	7.97	7.32	7.76	8.48	7.42	8.34	9.04
1:12	6.97	8.17	7.25	8.00	7.41	7.89	8.53	7.42	8.42	9.10
1:14	7.00	8.23	7.28	8.05	7.53	7.94	8.64	7.54	8.49	9.16
1:19	7.08	8.31	7.30	8.13	7.61	8.02	8.79	7.61	8.55	9.24
1:25	7.17	8.67	7.41	8.72	7.75	8.18	8.86	7.71	8.68	9.32

RÔLE OF $CaCO_3$ IN SOIL REACTION

The effect of a slightly soluble substance like $CaCO_3$ on soil reaction needs special attention. It is conceivable that even in the absence of other salts, $CaCO_3$ would modify the soil reaction, even in the presence of *N* KCl. This was actually observed both in natural calcium soils and in soils to which $CaCO_3$ was added and which without $CaCO_3$ had shown no effect of soil-water ratio

in *N* KCl (table 5). The results given in table 6 show that the effect of soil-water ratio persists even in *N* KCl on soils containing $CaCO_3$. For such soils, therefore, the soil-water ratio will still have to be defined even when pH values are determined in *N* KCl.

SUMMARY

The effect of salts and soil-water ratio on soil reaction has been studied.

The salts have a profound influence on soil reaction, which alters appreciably in the presence of even small quantities of neutral salts.

The effect of soil-water ratio on soil reaction is indirect insofar as the soil-water alters the concentration of salts present.

In the absence of salts, the pH value is not affected by soil-water ratio.

Since natural soils contain varying amounts of salts, uniformity of results can only be obtained by determining soil reaction in *N* KCl solution.

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A THEORY EXPLAINING THE RELATION OF SOIL–WATER RATIOS TO pH VALUES[1]

CLARK M. KEATON[2]

Washington State Agricultural Experiment Station

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In the determination of soil reaction or pH values, the use of a highly artificial condition which never exists in the field is a commonly accepted practice. High dilutions of soil to water are used because of the type of apparatus which is employed for hydrogen-ion determinations and because of the fact that only at high ratios of soil to water are constant values for the same soil obtained. The exact ratio of soil to water employed varies with the different investigators. The literature on the ratio and the effect of dilution is voluminous, but there is actually little correlation among the results of the different investigators. Some report an increase in acidity with dilution, others find an increase in alkalinity, and still others find no change in pH. The general trend, as shown by the referee report of McGeorge (5), is toward an increase in pH with dilution.

With the introduction of the glass electrode and its subsequent development, hydrogen-ion determinations may now be made at a much lower ratio of soil to water. Using a colorimetric method, Wilcox (10) measured the pH of the displaced solution at soil moisture-holding capacity. Heintze (1) was able to determine the pH of soils at their sticky point, but because of the type of glass electrode used, he was unable to get a good contact between the soil and electrode at a lower moisture content. McGeorge (4), with the use of the Beckman Spear-Type glass electrode, has shown that it is possible to obtain the pH values of semiarid soils with as low a moisture content as 6 per cent. It now appears probable that the soil reaction may be ascertained under field moisture conditions instead of under the highly artificial state established in the laboratory. In this study, the reaction of representative soil types of the State of Washington was determined at the normal field moisture content and compared with the values at higher dilutions of soil to water.

PROCEDURE AND RESULTS

A moisture content approximating that of the normal moisture percentage of the soils used was obtained by carefully tamping air-dried soil passed

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through a 2 mm. sieve in 100 cc. graduate cylinders, and adding CO_2-free distilled water in small increments until approximately 2 inches of dry soil remained in the bottom of the cylinder. The cylinders were then tightly stoppered and allowed to stand undisturbed for 48 hours until approximate moisture equilibrium conditions were established. In a later study it was found that although a period of 36 hours was sufficient for complete penetration of the water in all soil types, a slow distribution continued, so that the moisture content obtained even at 48 hours, especially in the heavier soils, was slightly higher than the normal moisture percentage.

The hydrogen-ion concentration was determined by transferring the moist soil to a small beaker and gently pressing it around a special calomel type glass electrode made by the author. The electrode, as described by Peech (7), consisted of a saturated calomel electrode inserted in a short length of 0.015 Corning glass, which had a thin bulb blown at one end. Contact was made by means of a mercury connection, the whole electrode being a single complete unit when assembled. The moisture content of the soil was determined immediately after the pH values were determined. Values of the hydrogen-ion concentration of the same soils were determined in soil-water ratios of 1:10, 1:5, and 1:1, CO_2-free distilled water being used in all soil suspensions. The resulting values for the representative soils are given in table 1.

The condition under which the soil reaction is determined evidently has a great influence on the magnitude of the pH value obtained. As the soil-water ratio narrows to 1:1, the pH value of the soil decreases. This is in accordance with the findings of other investigators (3, 5, 8, 9) and may be explained by the increase in hydroxyl ions on dilution. The Debye and Hückel activity theory must also be considered. As the soil-water ratio becomes narrower, the concentration of the ions in the soil suspension will increase with subsequent decrease in ion activity.

When the soil reaction is determined at approximately normal moisture conditions, the decrease in pH values with decreasing moisture content is no longer continued in all soils. The decrease continues only in those soils which are approximately neutral, but in the more acid soils the pH values increase at approximately normal field conditions as compared to a 1:1 ratio of soil to water. In several of these acid soils the resulting values at the normal moisture percentage are higher than those obtained at a 1:5 ratio, and in a few exceptional soils they are higher than those at a 1:10 ratio. Wilcox (10) also found an irregular change in pH values with soil-water ratios in different soils. In four of the six soils listed by him, the pH values increased at the moisture-holding capacity as compared to higher dilutions.

Before any explanation of this phenomenon was attempted, it was thought advisable to determine whether this change in pH was observable in soils representing different extreme types. The values for these different soils are given in table 2. When an excess of water is present in these soils, as in

those previously examined, a decrease in the pH values occurs with a decrease in the soil-water ratio. At approximately normal moisture percentage the values of the alkaline and neutral soils continue to decrease, whereas those of the acid soils increase or decrease as compared to a 1:1 ratio of soil to water.

TABLE 1

pH values at different soil-water ratios of representative soil series in the State of Washington

SOIL NUMBER	SOIL SERIES	RATIO 1:10	RATIO 1:5	RATIO 1:1	NORMAL MOISTURE	NORMAL MOISTURE
		pH	*pH*	*pH*	*pH*	*per cent*
1	Hesson	5.50	5.31	5.24	5.47	46.46
2	Felida	6.24	5.93	5.74	5.92	32.20
3	Everett	5.71	5.77	5.38	5.88	32.99
4	Puget	5.77	5.54	5.35	5.51	35.75
5	Chehalis	5.68	5.48	5.19	5.25	70.95
6	Melbourne	5.08	4.92	4.68	5.34	59.10
7	Salkum	5.72	5.49	5.46	5.60	33.21
8	Olympic	5.66	5.56	5.25	5.69	54.29
9	Walla Walla	6.25	6.32	5.86	5.32	25.81
10	Hoquiam	5.06	4.95	4.81	5.31	52.53
11	Spanaway	5.78	5.71	5.43	5.99	24.78
12	Garrison	7.22	7.14	6.80	6.25	29.27
13	Ephrata	7.30	7.00	7.02	6.82	24.00
14	Cashmere	6.98	6.98	6.68	6.91	17.65
15	Palouse	6.81	6.60	6.33	6.03	26.73
16	Ritzville	6.19	5.97	5.56	5.71	30.11
17	Lynden	5.74	5.83	5.56	5.77	18.37

TABLE 2

pH values at different soil-water ratios

SOIL NUMBER	SOIL	RATIO 1:10	RATIO 1:5	RATIO 1:1	NORMAL MOISTURE	NORMAL MOISTURE
		pH	*pH*	*pH*	*pH*	*per cent*
18	Alderwood (Washington)	5.17	4.92	4.82	5.34	30.06
19	Podzolic (Washington)	5.64	5.83	5.65	5.48	26.94
20	Mohave (Arizona)	8.35	8.42	7.96	6.71	18.13
21	Lakewood (New Jersey)	4.74	4.56	4.04	4.05	24.50
22	Greenville (Florida)	5.75	5.70	5.39	5.19	20.66
23	Houston (Texas)	8.32	8.08	7.51	6.58	54.02
24	Barnes (North Dakota)	7.64	7.44	7.07	6.82	47.17
25	Black Alkali (Washington)	10.17	10.04	9.82	8.40	35.69

Mattson (6) has shown that the exchangeable ions in the colloidal micelle have varying degrees of dissociation, depending on their hydration and electrostatic forces. Their order of dissociation, in general, follows the Hofmeister series. When the soil-water ratio is such that free water is present, the exchangeable ions have a high degree of dissociation. At approximately

normal moisture percentage, insufficient water is present to allow as high a degree of dissociation of the exchangeable cations; therefore, preferential dissociation results, in which those ions which dissociate most readily dissociate to the greatest degree. Thus there will be a preferential dissociation of the metallic cations over the hydrogen ions. As the pH of the soil suspension is dependent upon the concentration and type of ions dissociating from the colloidal micelle, the pH value of the soil suspension will be higher in the case of preferential dissociation than in the case of complete dissociation. Jarusov (2) has shown, however, that certain factors such as organic matter, degree of saturation, and kinds of exchangeable cations influence the mobility of the exchangeable cations in the soils. For this reason, in certain soils hydrogen may be more mobile than the metallic cations, with the result that preferential dissociation will cause a lower pH value instead of a higher.

Another influence on the pH values of the soil suspension is the Debye Hückel activity effect, which is a function of the valence and concentration of the ions in the soil suspension. Thus both preferential dissociation and the Debye Hückel activity effect may serve as a basis for explaining the difference in pH value occurring at the normal moisture content as compared to the 1:1 ratio of soil to water. In the alkaline and neutral soils the concentration of the metallic cations is such that the Debye Hückel activity effect will overshadow any effect of preferential dissociation of the metallic cations over hydrogen. In the acid soils that exhibit an increase in the pH values, the preferential dissociation of the metallic cations over hydrogen predominates. The few acid soils that show a continued decrease in the pH values may be the result of a condition in which the hydrogen is more mobile than the metallic cations.

In order to substantiate the theory, two soils were prepared in which only two different types of cations, hydrogen and calcium, or hydrogen and sodium, were present in the micelle. If the theory of preferential dissociation is valid, there should be a ratio of the metallic cations to the hydrogen ions at some low moisture range at which, because of the effect of preferential dissociation, an increase in pH would result upon a further decrease in the moisture content.

A soil was completely desaturated by leaching with 0.05 *N* HCl; its total base-exchange capacity was determined with ammonium acetate; and different portions were saturated to different degrees with Ca or Na by the addition of the proper amounts of calcium or sodium hydroxide. The reaction of these variously saturated soils was determined at different soil-water ratios and at approximately normal moisture percentage. The data are recorded in table 3, in which the same phenomenon is demonstrated as was exhibited in the natural soils. Below 50 per cent base saturation, there is an increase in the pH values at normal moisture percentage as compared to a soil-water ratio of 1:1.

Both the artificially prepared soils and the soils in their natural condition substantiate the theory of preferential dissociation. In general, the acid

soils increase in pH values as a result of a decrease in the moisture content of the soil from a 1:1 ratio to normal moisture capacity, indicating a dominance of preferential dissociation. The pH values of the alkaline and neutral soils continue to decrease, showing that in these soils the "activity effect" is greater than the effect of preferential dissociation.

At approximately normal moisture percentage, as compared with higher moisture contents, the increase in pH in the podzol and lateritic soils is negligible, as would be expected from the theory of preferential dissociation. Since these soils are nearly completely desaturated, the hydrogen ions dominate in the micelle and soil suspension. Thus, both the effect of preferential dissociation and the Debye Hückel activity effect will be opposite, small, and nearly equal. This is shown in the values obtained for these two soils. A slight reduction in the pH values takes place in the lateritic soil; in the podzol a neutralization of the two factors occurs, with the pH value remaining constant.

TABLE 3

Effect of percentage base saturation on pH values at different soil-water ratios

TREATMENT	RATIO 1:10	RATIO 1:5	RATIO 1:1	NORMAL MOISTURE
	pH	*pH*	*pH*	*pH*
100 per cent Ca saturation	6.90	6.85	5.73	5.68
75 per cent Ca saturation	6.27	6.27	5.38	4.98
50 per cent Ca saturation	5.18	5.13	4.36	4.25
25 per cent Ca saturation	4.42	4.17	4.02	4.12
10 per cent Ca saturation	4.43	4.05	3.86	3.94
0 per cent Ca saturation	3.75	3.77	3.75	3.89
100 per cent Na saturation	7.10	6.98	6.00	6.10
75 per cent Na saturation	6.83	6.70	5.94	5.89
50 per cent Na saturation	5.76	5.59	4.86	4.91
25 per cent Na saturation	5.37	5.10	4.42	4.52
10 per cent Na saturation	4.76	4.45	4.00	4.27
0 per cent Na saturation	4.00	3.75	3.80	3.89

In a soil which exhibits the influence of the counteraction of the Debye Hückel activity effect and the effect of preferential dissociation, there should be a soil-water ratio at which the pH value is at a minimum. At this ratio the amount of water present in the soil suspension would be just sufficient for a high dissociation and concentration of the cations in the micellar solution. This point should lie just below the maximum water-holding capacity of the soil. Several soils were selected to determine whether this point of minimum pH value could be attained. The total pore space was calculated from the volume weight of the respective soils. Sufficient water was added to bring them just to saturation. The reactions were measured, and the results, recorded in table 4, indicate that the pH value obtained at the point of saturation is lower than that for any other soil-water ratio of these respective soils.

The theory of preferential dissociation explains the increased pH values of certain soils at approximately normal moisture percentage as compared to those at higher soil-water ratios. The data from the artificially prepared soils and the minimum pH values obtained at moisture saturation strongly support the theoretical considerations. As the counteraction between the "activity effect" and preferential dissociation due to changes in moisture content will be a factor in the seasonal fluctuations in the pH of soils under natural field conditions, the pH value of the soil obtained at the normal moisture content is more representative of the soil reaction under field conditions and appears to give a truer picture of the actual conditions under which plants grow than the values obtained under the highly artificial conditions now employed.

TABLE 4

Soil-water ratios showing a point of minimum pH

SOIL NUMBER	RATIO 1:10	RATIO 1:5	RATIO 1:1	SATURATION	NORMAL MOISTURE
	pH	*pH*	*pH*	*pH*	*pH*
3	5.71	5.77	5.38	5.19	5.88
6	5.08	4.92	4.68	4.37	5.34
11	5.78	5.71	5.43	5.36	5.99
18	5.17	4.92	4.82	4.65	5.34

SUMMARY

The determination of the pH values of several soils at different soil-water ratios, ranging from a ratio of 1:10 to approximately normal moisture capacity, shows that the condition under which the soil reaction is determined by the use of a glass electrode has a pronounced influence on the pH value obtained.

In acid soils the minimum pH value occurs when the soil-water ratio is at the point of the water-holding capacity of the soil. A further reduction in the soil moisture content results in increased pH values because the proportion of metallic cations to hydrogen ions is low enough to produce a counteraction of the Debye Hückel activity effect by the effect of preferential dissociation.

In the more alkaline soils, the proportion of metallic cations is much higher than that in acid soils; therefore, the "activity effect" overshadows the effect of preferential dissociation, with the result that a continued decrease in pH values takes place with decreasing moisture content.

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ON THE FORMATION OF STRUCTURE IN SOIL: V. GRANULAR STRUCTURE

D. I. SIDERI

Agricultural Institute, Voronezh, U. S. S. R.

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The prevailing conception of structure formation in soil tends to limit this process to a definite range of phenomena and to associate it with the genesis of various soils. Structure thus assumes the character of a general property of soil and the significance of an organizational symptom closely connected with the chemical and physical properties of soil. Questions of morphogenesis are still unexplained, however, and information of but the most general character is available concerning the relation of the form of structural aggregates to the inherent properties of soil. The purpose of this paper is to summarize some results of the author's studies on the origin of structural forms in connection with the alteration of the composition of soil. Although it is not yet possible to explain all the various forms, the theoretical investigation of this problem may have a practical application.

The greatest interest is presented by the durable granular structure possessed mainly by the upper layers of humus-rich soils. The typical granularity of such soils is distinguished by the black color and the considerable solidity and size (3–7 mm.) of the grains (2) and by the shape of the structural aggregates, which manifests itself in the formation of small clods, some of which are spheric, and some of which have irregular, angular surfaces.

Granular structure is altered or destroyed by certain factors. As has been noted, the accumulation of sand in chernozem weakens and destroys the structure, and this action is readily explained by conditions which affect the state of equilibrium (4). In regions of solonetz soil, typical granular structure is transformed into a "cloddy-granular" or even a "prismatic-granular" structure (2), in which the grains become more compact and acquire a pronounced brilliancy and an angular surface. In dry steppe chernozems, the grains become less compact as a result of the insignificant quantity of humus in the soils; their color changes to brown. The size of the grains decreases, and in some places granularity disappears completely, the structure passing into another type—the laminar (2). Loss of typical granularity takes place in the process of podzolization of chernozems. At certain stages of degradation, accompanied by the destruction of a part of the organic matter content, "granularity is still preserved, but the grains lose their compactness and form" (2). With increased decomposition of organic substance, "the clarified mass of the soil, on drying, begins to break up into laminar fragments" (2).

The inverse process of the restitution of structure in those soil layers in which it has been destroyed, is also observed in nature. Thus, "forest-steppe soils, possessing a laminar structure, become granular when their humus content increases as a result of encroachment of steppe vegetation upon forest areas" (2). It is a well-known fact, as well, that pulverized arable soils regain granularity under the influence of perennial meadow vegetation.

Both phenomena—the destruction and the restitution of granular structure —deserve most serious attention and study (2). The explanation of the origin of granular structure and of the processes involved in its destruction may be based on the study of relative states of equilibrium in sand-clay-humus mixtures. Important circumstances which may be of service in the elucidation of these phenomena are as follows:

The appearance of the *spheric* and *laminar* forms is the extreme manifestation of the symptoms of restitution and destruction of granular structure.

In the restitution and destruction of granular structure there is a gradual transition from one form to the other, and this transition is invariably related to the alteration in the content of organic matter.

The sand-clay-humus mixture having an excess humus content is an unstable system. When such a mixture is dried or frozen, it separates into two distinct parts (pl. 1). One of these, the anisotropic, consists of laminar particles of humus-clay-sand. The other is organic matter, which separates from the mixture after clay is "saturated" with humus. The disintegration of the mixture results from the difference in the surface tension of its components. The anisotropic component is a medium of high viscosity and comparatively low surface tension; the organic, isotropic component has the same capillary constant as water. Because of this difference in surface tension, the organic matter must distribute itself at the periphery of the anisotropic substance, which occupies the central position. According to the theory of Curie (1), the capillary constant of isotropic substance is the same in every direction, and this condition corresponds to *a minimum surface or to the spheric form.* Consequently, amorphous organic substance, distributed at the periphery of a structural aggregate, determines the shape of the latter. Such an aggregate must possess a spheric or a nearly spheric form. The inner part of the structural aggregate is a crystalline substance with a minimal surface tension, and it must, therefore, have a flat surface and a polyhedric form. Since the disintegration takes place long before the solidifying of the medium, while the latter is still viscous, the mechanical resistance does not exceed the surface tension, a situation which makes possible the application of the theory of Curie to a system of this kind. At the surface of delimitation—organic substance-air—the superficial rows of micellas of the organic matter are oriented and form a semipermeable layer (4). The formation as a whole, that is, the soil aggregate, is a kind of cell, possessing osmotic properties. The spheric form of granular structure is a sign of the accumulation of an amorphous

layer of humus at the periphery, as a result of which the granular aggregates have an immense surface enclosed in a small volume.

The destruction of granularity must be accompanied by the elimination of the surface layer of amorphous organic matter. As this layer is gradually eliminated, the polyhedric form of the inner anisotropic substance becomes more and more apparent, and the gradual transition to the cloddy-granular or prismatic-granular structure of the weakly solonetz and weakly degraded chernozems occurs. If this process of degradation is intensified, however, and the destruction of this humus layer progresses, the soil mass becomes laminated (3).

Granularity is destroyed also during the plowing and cultivating of soil. The process of destruction is related not only to the direct action of the implement, but also to the resulting change in the normal distribution of the aggregates in the soil layer. Under the influence of the atmosphere, of the changes in the conditions of aeration, of the change of vegetation and microorganisms, the oriented layer of organic substance at the surface of the aggregate is destroyed. The state of equilibrium of the amorphous layer of humus is unsettled, and the separation into smaller parts takes place. The fact that the rapid rate at which structure is destroyed under the influence of tillage is out of all proportion to the decrease of the supply of humus in soil, bears out this interpretation (2). As has been noted by many investigators, the humus supply, by itself, does not ensure a stable granular structure. A necessary condition for the formation of stable aggregates is *the formation of a metastable envelope of oriented substance at the surface of the amorphous humus layer, which preserves the microaggregate from division* (3, 4).

The process of the restitution of granular structure consists in the formation of a layer of amorphous organic substance around a laminar aggregate. The permeation of the aggregate, already existing in the soil, by organic matter and the accumulation of firmly bound humus are determined by the state of equilibrium of the anisotropic lamina. Beyond this limit there is no binding of humus, and the excess organic matter gathers at the *periphery* of the lamina, transforming it into a granular aggregate. It is to be presumed, therefore, that the formation of grains depends not so much on the action of the root-system of grass, as on the accumulation of amorphous humus under perennial meadow vegetation.

SUMMARY

The interpretation of the form of the structural elements of chernozem soils can be based on the study of the decomposition of the complex mixed sand-clay-humus formations.

The form of the typical granular structure of chernozem is a sign of the accumulation of amorphous humus at the periphery of the aggregate.

Increase of the exchange capacity of soil must be closely connected with the appearance of amorphous humus at the periphery of the aggregate. If

organic matter is firmly bound with clay as an anisotropic formation, no marked increase in the adsorption capacity occurs.

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PLATE 1

DISINTEGRATION OF THE SAND-CLAY-HUMUS MIXTURE

The Oriented Layer of Humus
The Anisotropic Mixture Sand-Clay-Humus
The Isotropic Humus